Enantioselective Synthesis of *P*-Chiral (η^6-Arene)ruthenium(II) Complexes Using Enantiomerically Pure Orthometalated Palladium(II) Amine Complexes

Kesete Y. Ghebreyessus, Nizamettin Gül, and John H. Nelson*

Department of Chemistry/216, University of Nevada−Reno, Reno, Nevada 89557-0020

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Enantiomerically pure, rigid, diphosphines [2-(dicyclohexylphosphino)-5,6-dimethyl-7-phenyl-7-phosphabicyclo[2.2.1]hept-5-ene, [2-(diphenylphosphino)-5,6-dimethyl-7-phenyl-7-phosphabicyclo[2.2.1]hept-5-ene, and the amidophosphine [2-(*N*,*N*-dimethylamido)-5,6-dimethyl-7-phenyl-7-phosphabicyclo[2.2.1]hept-5-ene were prepared efficiently, by the asymmetric Diels−Alder reactions between dicyclohexylvinylphosphine (DCVP), diphenylvinylphosphine (DPVP), *N*,*N*-dimethylacrylamide (DMAA), and 3,4-dimethyl-1-phenylphosphole (DMPP) using chiral organopalladium(II) complexes containing orthopalladated (*S*)-1-α-(dimethylamino)ethylbenzene, (*R*)-1-α-(dimethylamino)ethylnaphthalene, or (*S*)-2-α-(dimethylamino)ethylnaphthalene as the reaction templates. Treatment of the diphosphine complexes with concentrated hydrochloric acid removed the chiral amine auxiliaries from the templates to give chelated dichloropalladium complexes. Then the ligands were displaced from the palladium chloride complexes with cyanide and reacted with [(η^6-1,3,5-$Me_3C_6H_3$)-Ru)Cl_2]$_2$ in the presence of $AgCF_3SO_3$ to form enantiomerically pure [(η^6-1,3,5-Me_3C_6-H_3)Ru(II)(P∼P)Cl]CF_3SO_3 complexes, chiral at ruthenium. Similarly, treatment of the amidophosphine palladium complexes with 1,2-bis(diphenylphosphino)ethane in dichloromethane liberated the enantiomerically pure *P*-chiral ligands, which reacted with [(η^6-*p*-cymene)$RuCl_2$]$_2$ in the presence of $AgCF_3SO_3$ to form an inseparable mixture of two diastereomers of [(η^6-*p*-cymene)Ru(II)(P∼O)Cl]CF_3SO_3, chiral at ruthenium. The complexes have been characterized by elemental analyses, circular dichroism, ^{1}H, ^{31}P{^{1}H}, and ^{13}C-{^{1}H} NMR spectroscopies, and in several cases X-ray crystallography.

Introduction

Chiral bidentate phosphines have become an important class of ligands in homogeneous asymmetric catalysis due to their outstanding ability to form highly active and selective catalysts with transition metals.[1] Hence, great interest is directed toward the design and efficient syntheses of chiral phosphines.[2,3] The synthesis of chiral phosphines usually involves the separation of racemic mixtures by resolving methods that are tedious and expensive.[4] Another approach to the synthesis of chiral phosphines, without resolution or separation of diastereomers, entails asymmetric Diels−Alder cycloaddition reactions.[5] The Diels−Alder cycloaddition is one of the most widely used methods to synthesize simple and complex ring systems due its ability to create up to four stereogenic centers in a highly stereoselective and predictable manner.[6,7] In this context, Leung and coworkers have showed that the optically pure orthopalladated [1-α-(dimethylamino)ethyl]naphthalene can act as a chiral template to promote the asymmetric Diels−Alder reaction between 3,4-dimethyl-1-phenylphosphole (DMPP) and a variety of dienophiles within the coordination sphere of palladium.[8]

On the other hand, we have prepared racemic conformationally rigid [(η^6-arene)Ru(II)(A−B)Cl]X (where A−B is an asymmetric bidentate ligand and X = PF_6^- or $CF_3SO_3^-$) complexes with high diastereoselectivity

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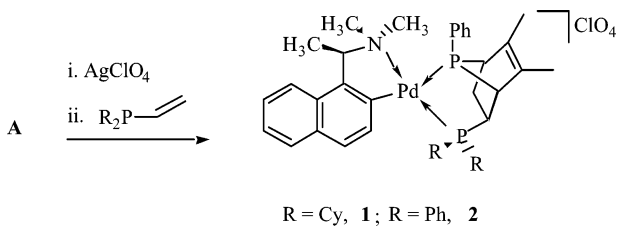
by intramolecular Diels−Alder cycloaddition between coordinated 3,4-dimethyl-1-phenylphosphole (DMPP) and a variety of dienophilic ligands.[9] Ruthenium becomes a stereogenic center in the process and can have either *R* or *S* configuration. Because there is no asymmetric induction in this case, the products formed are racemic. These complexes (with triflate as a counterion) have been found to be quite efficient catalysts for the transfer hydrogenation of ketones in 2-propanol in the presence of KOH.[9b] Thise findings encouraged us to synthesize enantiomerically pure forms of these complexes and investigate their application as catalysts for asymmetric transfer hydrogenation of ketones. Recently, the synthesis of half-sandwich enantiomerically pure chiral at metal ruthenium(II) complexes has attracted considerable interest.[10] They have been shown to be promising catalysts for a variety of organic transformations.[10] Hence, the work presented here was undertaken (i) to explore the influence of the order of ligand coordination on the diastereo- and enantioselectivities of the enantiomerically pure orthopalladated complex mediated Diels−Alder cycloadditions, (ii) to synthesize and characterize conformationally rigid, enantiomerically pure *P*-chiral (η^6-1,3,5-$Me_3C_6H_3$)Ru(II) and (η^6-*p*-cymene)Ru(II) complexes using these templates, and (iii) to explore the enantioselectivity in catalytic transfer hydrogenations catalyzed by these ruthenium complexes.

Results and Discussion

A convenient access to conformotionally rigid *P*-chiral diphosphine and tertiary amide functionalized monophosphine ligands was achieved by means of palladium complex promoted asymmetric Diels−Alder reactions. These *P*-chiral 7-phosphanorbornene complexes **1**−**3** (Scheme 1) were prepared by successive treatment of the chloro species (R_C)-**A** and (S_C)-**B** (Chart 1) with stoichiometric quantities of aqueous silver perchlorate in dichloromethane followed by the addition of the corresponding vinyl phosphines (DCVP, DPVP) directly into the solution upon removal of silver chloride.

Complexes **2**[8b] and **3**[8a] have been previously reported. The spectroscopic data (^{1}H, ^{13}C{^{1}H}, ^{31}P{^{1}H} NMR) are

Scheme 1



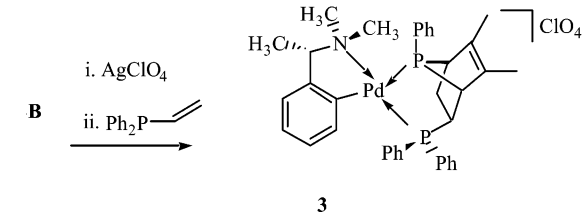
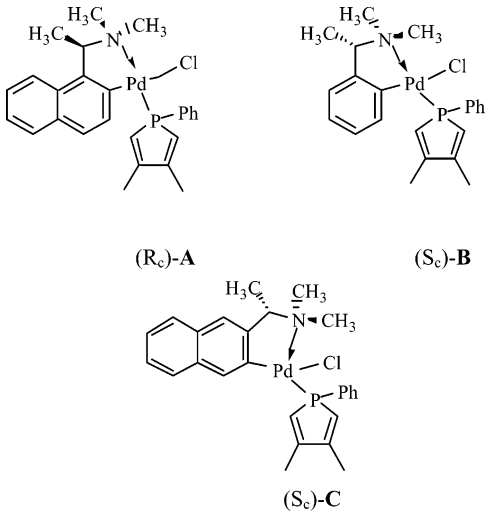


Chart 1



in agreement with those reported. Similar to **2** and **3** the ^{31}P{^{1}H} NMR spectrum of **1** exhibits only two sets of doublets at (δ, 118.40, 70.37 ppm, ^2J(PP) = 37.4 Hz), indicating the presence of only a single diastereomer. The low-field resonance is typical of the bridgehead phosphorus adopting the *syn-exo*[8,9,11−13] stereochemistry. In the ^{1}H NMR spectrum the methyl protons of the NMe_2 group display two different resonances (at δ 2.51, 2.36 ppm with ^4J(PH) = 3.0 and 1.5 Hz), as they are diastereotopic.[12b]

The molecular structure of **3** has already been reported,[8a] and that of **1** is given in Figure 1. X-ray quality crystals of **1** were obtained by slow diffusion of

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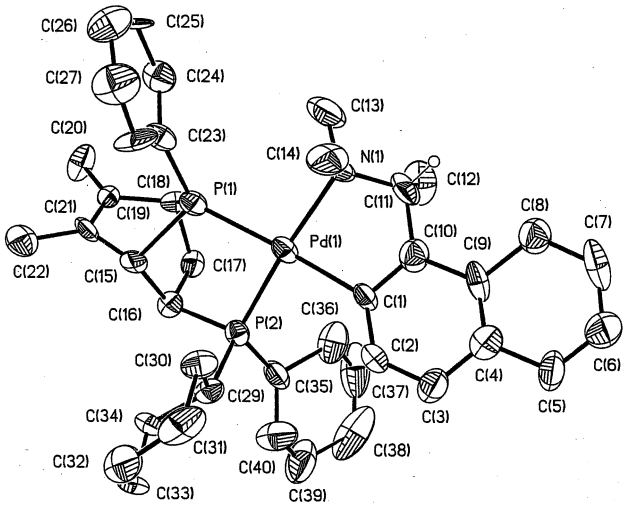


Figure 1. Structural drawing of **1** showing the atom-numbering scheme (30% probability thermal ellipsoids). Hydrogen atoms are omitted for clarity.

ether into a dichloromethne solution. Crystallographic data and selected bond distances and angles are presented in Tables 1 and 2, respectively. The coordination geometry around palladium is approximately square planar with the Cy_2P moiety (softer donor atom) *trans* to the NMe_2 group, while the bridgehead phosphorus is *trans* to the aromatic carbon atom of the naphthylamine ligand. The metrical parameters resemble those previously reported for related orthometalated Pd(II) complexes.[8a,f] The angles around palladium range from 81.1(5)° for N−Pd−C to 100.8(4)° for N−Pd−P(1) and 174.8(3)° for P(1)−Pd-C(1) to 176.2(4)° for N−Pd−P(2). The Pd−P(1) and Pd−P(2) bond lengths are 2.333(3) and 2.260(4) Å, respectively. The Pd−P bond *trans* to the nitrogen is shorter than that *trans* to carbon. This effect is associated with the lengthening of the Pd−C bond to 2.081(12) Å; a typical value of 1.98 Å was observed for related naphthylamine complexes.[8d] The absolute configurations of the four stereogenic centers *S* at P(1) and C(16) and *R* at C(15) and C(18), respectively, were assigned from the molecular structure.

As illustrated in Scheme 2, two procedures may be used to synthesize **3a**. Usually the synthetic approach used in these Diels−Alder cycloaddition reactions involves initial activation of the vinylphosphine by coordination to the orthometalated palladium(II) amine complex (route I).[8a,b,f] A dichloromethane solution of the resulting complex was then treated with a stoichiometric quantity of aqueous silver perchlorate. Upon removal of silver chloride the in situ generated perchlorato complex was treated with stoichiometric amounts of DMPP to give the enantiomerically pure diphosphine-coordinated Pd(II) complex (e.g., complex **3a**). The resulting bidentate ligands coordinate regiospecifically to the orthometalated palladium(II) amine complex,

Table 1. Crystallographic Data and Structure Refinement for 1, 6, 7, and 8b and 5b, 8a, 10, 12a, and 12b

	1	**6**	**7**	**8b**
formula	$C_{44}H_{64}ClNO_5P_2Pd$	$C_{18}H_{22}F_6N_3PPd$	$C_{14}H_{20}F_6N_3PPd$	$C_{31}H_{38}F_6N_2OP_2Pd$
MW	890.75	531.76	481.70	736.97
cryst syst	orthorhombic	orthorhombic	orthorhombic	orthorhombic
space group	$P2_12_12_1$	$P2_12_12_1$	$P2_12_12_1$	$P2_12_12_1$
a (Å)	10.3523(14)	8.7194(6)	7.8452(13)	11.5205(16)
b (Å)	14.234(3)	17.3434(16)	11.6780(8)	13.878(4)
c (Å)	30.640(60	13.311(6)	20.9553(14)	20.220(4)
Z	4	4	4	4
α (deg)	90	90	90	90
β (deg)	90	90	90	90
γ (deg)	90	90	90	90
volume (Å^3)	4514.9(13)	2233.0(3)	1919.8(4)	3232.9(12)
ρ_{calcd} (mg/m^3)	1.310	1.582	1.667	1.514
no. of reflns collcd	5572	2945	2602	4037
no. of ind reflns	5316	2754	2415	3835
R1[a]	0.0690	0.0417	0.0774	0.0431
wR2[b]	0.1332	0.0854	0.1877	0.0948
GOF	1.062	1.037	1.094	1.023

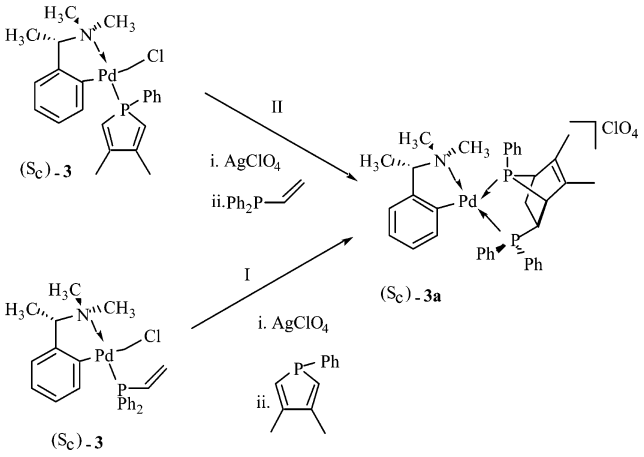
	5b	**8a**	**10**	**12a**	**12b**
formula	$C_{27}H_{36}ClN_2O_5PPd$	$C_{31}H_{38}F_6N_2O_2P_2Pd$	$C_{27}H_{42}Cl_2OP_2Pd$	$C_{36}H_{38}ClF_3O_3P_2RuS$	$C_{36}H_{38}ClF_3O_3P_2RuS$
MW	641.40	752.97	621.85	806.18	806.18
cryst syst	triclinic	monoclinic	orthorhombic	monoclinic	monoclinic
space group	$P\bar{1}$	$P2_1$	$P2_12_12_1$	$P2_1$	$P2_1$
a (Å)	9.242(3)	9.4740(18)	10.1963(9)	11.1265(7)	11.1387(13)
b (Å)	9.746(4)	19.2318(18)	13.9046(18)	13.1882(10)	13.1999(17)
c (Å)	10.099(4)	10.5801(11)	20.358(4)	12.287(3)	12.2946(140
Z	1	2	4	2	2
α (deg)	63.73(2)	90	90	90	90
β (deg)	64.32(3)	10.887(13)	90	96.999(8)	97.010(9)
γ (deg)	86.58(3)	90	90	90	90
volume (Å^3)	725.2(5)	1893.0(4)	2886.3(7)	1789.5(4)	1794.2(4)
ρ_{calcd} (mg/m^3)	1.469	1.321	1.431	1.496	1.492
no. of reflns collcd	2925	4366	2575	4204	4190
no. of ind reflns	2925	3664	2485	3612	3604
R1[a]	0.0613	0.0888	0.0647	0.0386	0.0356
wR2[b]	0.1260	0.2141	0.1207	0.0923	0.0833
GOF	1.062	1.052	1.037	1.058	1.046

[a] The data were refined by the method of full-matrix least squares on F^2, with the final *R* indices having $I > 2.00\sigma(I)$. $R1 = \sum||F_o| - |F_c||/\sum F_o$. [b] $wR2(F^2) = \{\sum[w(F_o^2 - F_c^2)]/\sum[w(F_o^2)^2]\}^{1/2}$.

Table 2. Selected Bond Distances (Å) and Bond Angles (deg) for 1, 8a, 8b and 5b

	1	8a	8b	5b
Pd−C(1)	2.081(12)	1.949(17)	1.998(6)	1.992(18)
Pd−N	2.163(11)	2.159(16)	2.163(5)	2.144(16)
Pd−P(1)	2.333(3)	2.222(5)	2.2149(16)	2.211(5)
Pd−P(2)	2.260(4)			
Pd−O		2.122(12)	2.118(5)	2.133(12)
N−Pd−C(1)	81.1(5)	82.4(7)	81.8(2)	82.5(7)
P(1)−Pd−C(1)	174.8(3)	97.6(5)	96.34(19)	96.4(5)
P(2)−Pd−C(1)	95.6(4)			
P(1)−Pd−P(2)	82.62(12)			
N−Pd−P(1)	100.8(4)	176.5(6)	173.4(2)	175.5(6)
N−Pd−P(2)	176.2(4)			
C(1)−Pd−O		174.2(8)	172.1(2)	168.3(7)
O−Pd−N		92.1(7)	91.5(2)	90.3(5)
O−Pd−P(1)		88.1(5)	90.81(13)	91.5(3)

Scheme 2



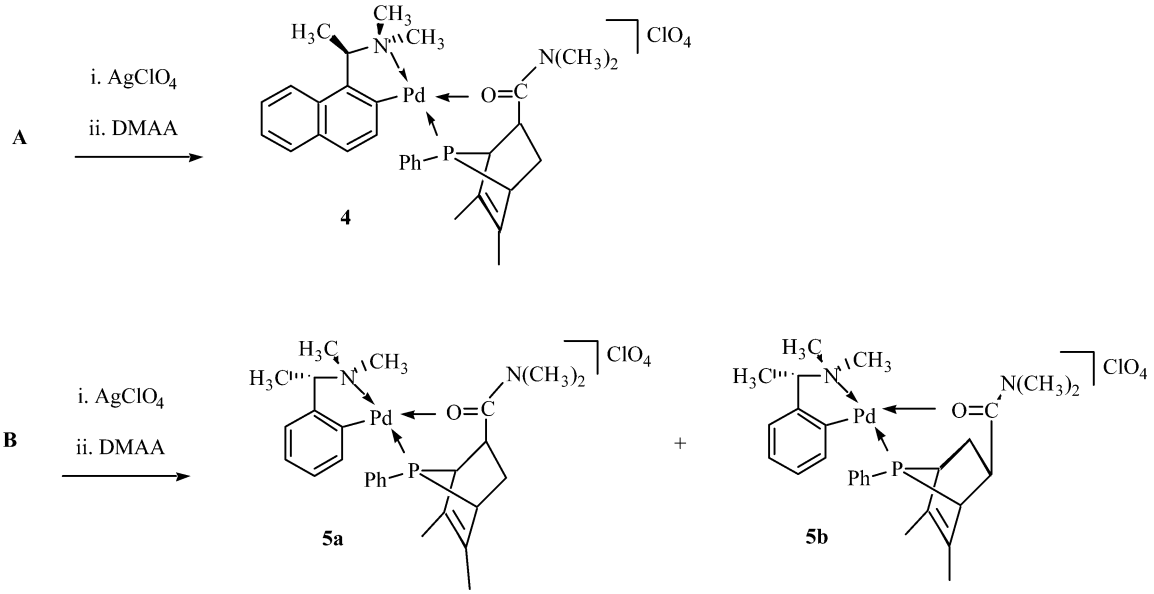
with the softer of the two donor ligands taking a position *trans* to the σ-donating NMe_2 group.

Alternatively, we considered it important to investigate the influence of the order of ligand activation on the stereochemical outcome in these cycloaddition processes. To examine this, the second synthetic approach (route II, Scheme 2) was employed. Thus, the 3,4-dimethyl-1-phenylphosphole was first activated by coordination to the orthometalated Pd(II) complex. A dichloromethane solution of the resulting complex was then treated with a stoichiometric quantity of silver perchlorate followed by the addition of the vinylphosphine. However, as shown in Scheme 2, the two synthetic approaches gave the same results regardless of the order of the substitution pattern of the orthometalated palladium(II) complex and do so with the same enantio- and diastereoselectivity. The crystal structure of **3a** has also been determined.[8a] The molecular structures revealed that the softer phosphine is *trans* to the NMe_2 group in the resulting square-planar complexes. These observations indicate a pronounced tendency for ligand substitution of the coordinated phosphole by softer ligands such as DCVP and DPVP prior to cycloaddition. The other orthometalated palladium(II) complexes (such as (S_C)-**A** and (S_C)-**C**) also react in the same manner. Similar ligand redistribution has previously been observed with analogous compounds containing *P*-chiral As−P bidentate ligands. Hence the reaction seems general for this type of ligand.[12]

The tertiary amide functionalized chiral phosphine complexes (R_C)-**4** and (S_C)-**5**[8c] (Scheme 3) were also synthesized in a similar way by adding DMAA to the in situ prepared perchlorate complex. These compounds ((R_C)-**4** and (S_C)-**5**) bear an oxygen functionality giving the phosphine a hybrid character. The formation of these complexes bearing four stereogenic centers occurs regio- and diastereoselectively with the five-membered orthopalladated amines, providing stereochemical control of the Diels−Alder cylcoaddition process.

The synthesis and characterization of (R_C)-**4** has been previously described and gave only a single diastereomer (Scheme 3).[8c] In contrast to (R_C)-**4** compound (S_C)-**5** is obtained as a mixture of two diastereomers, (S_C)-**5a** and (S_C)-**5b**, as evidenced by $^{31}P\{^1H\}$ NMR spectroscopy. Thus, prior to purification the $^{31}P\{^1H\}$ NMR spectrum of the crude product exhibited two singlets at δ 110.22 and 109.32 ppm in a ratio (S_C)-**5a**:(S_C)-**5b** of 1:2.3, respectively. The mixture was purified by fractional crystallization from CH_2Cl_2/ether solvents. After repeated purification the diastereomeric ratio changed to (S_C)-**5a**:(S_C)-**5b** = 1:9. However, although the presence

Scheme 3



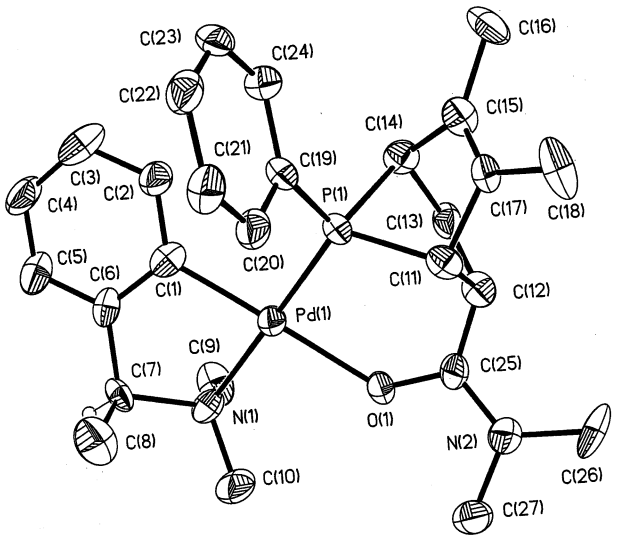
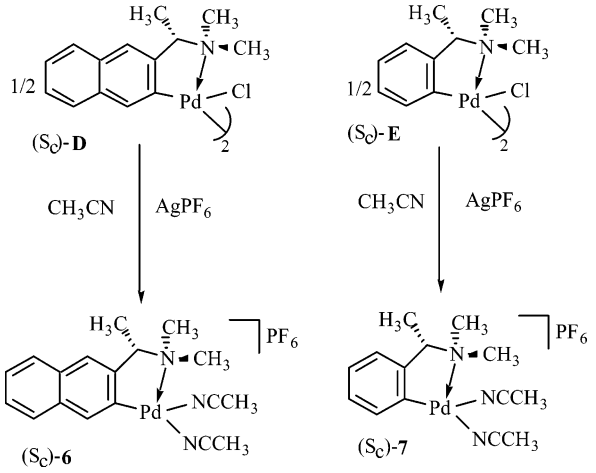


Figure 2. Structural drawing of **5b** showing the atom-numbering scheme (30% probability thermal ellipsoids). Hydrogen atoms are omitted for clarity.

Scheme 4



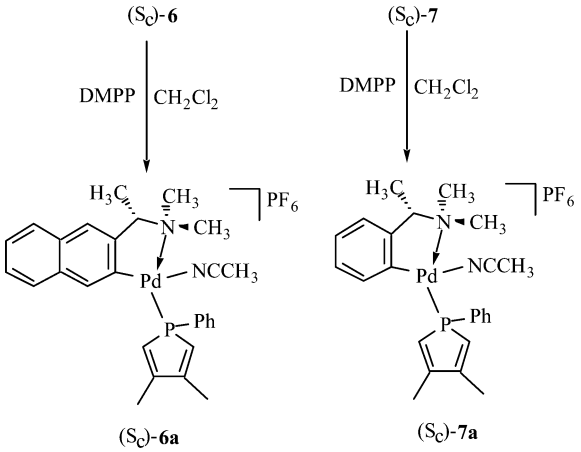
of both diastereomers was observed in solution, compound (S_C)-**5b** has been assigned to the major diastereomer by X-ray analysis of the crystallized material. A view of the structure of the cation of (S_C)-**5b** is shown in Figure 2. The absolute configurations of the four stereogenic centers of the major diastereomer (S_C)-**5b**, *R* at P(1), C(11), C(12), and C(14), respectively, were assigned from the molecular structure.

The chloride-bridged dimeric orthometalated palladium(II) amine complexes such as (S_C)-**D** and (S_C)-**E** are readily cleaved by a number of two electron donor ligands, such as tertiary phosphines, arsines, and CH_3-CN to give mononuclear products in good yields.[8,11,12] For instance, the monomeric chiral starting materials (R_C)-**A**, (S_C)-**B**, and (S_C)-**C** (Chart 1) were prepared by bridge cleavage of the dimers by DMPP. The Diels–Alder cycloaddition with DMPP also demands the simultaneous coordination of both the diene and the dienophile precursors to the chiral palladium template during the course of the carbon–carbon bond forming proseces.[13] Hence, the kinetically inert chloro ligand in the orthometalated palladium(II) amine complexes has to be replaced by the extremely labile perchlorato ligand prior to reaction with dienophiles.[8d] Alternatively, the

Table 3. Selected Bond Distances (Å) and Bond Angles (deg) for 6 and 7

	6	7
Pd–C(1)	1.912(19)	1.975(1)
Pd–N(1)	2.057(12)	2.062(6)
Pd–N(2)	2.006(12)	2.008(6)
Pd–N(3)	2.25(2)	2.124(6)
N(2)–Pd–C(1)	89.4(7)	94.7(3)
N(1)–Pd–C(1)	90.2(7)	81.8(3)
N(2)–Pd–N(1)	179.0(50	176.3(3)
N(3)–Pd–C(1)	177.6(7)	176.8(3)
N(2)–Pd–N(3)	92.9(6)	87.4(3)
N(1)–Pd–N(3)	87.5(6)	96.0(3)

Scheme 5

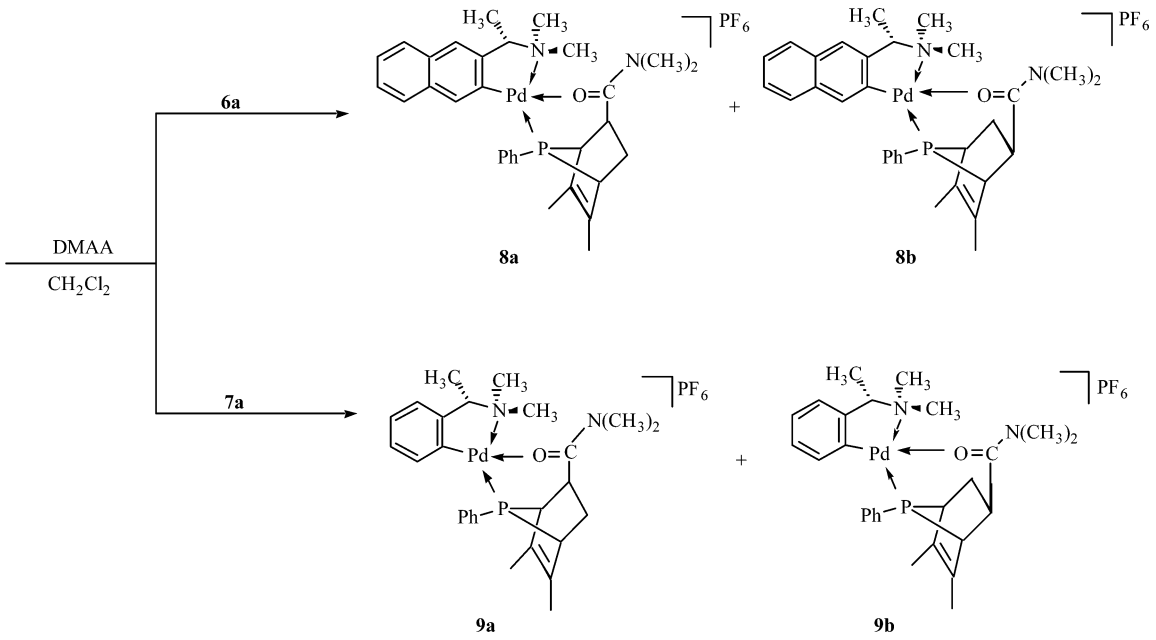


bis(acetonitrile) complexes (S_C)-**6** and (S_C)-**7** were prepared by bridge cleavage of the orthopalladated amine dimers (S_C)-**D** and (S_C)-**E** in acetonitrile in the presence of $AgPF_6$ (Scheme 4). These complexes containing the labile acetonitrile ligand could serve as alternative synthons to the reactive perchlorato complexes. Complexes (S_C)-**6** and (S_C)-**7** were characterized by ^1H, $^{31}P\{^1H\}$, and $^{13}C\{^1H\}$ NMR spectroscopy and X-ray crystallography. The ^1H NMR spectrum of each of the compounds showed two singlets for the acetonitrile methyl protons. The diastereotopic nature of the methyl protons of the NMe_2 group was also evident from the ^1H NMR data. This aspect was additionally confirmed by X-ray analysis. X-ray quality crystals of (S_C)-**6** and (S_C)-**7** were obtained by slow diffusion of ether into an acetonitrle solution. Crystal data and selected metrical parameters are given in Tables 1 and 3, respectively. The geometry at the palladium atom is nearly square planar, similar to analogous reported orthometalated palladium(II) amine complexes.[8] Views of the structures of (S_C)-**6** and (S_C)-**7** are given in the Supporting Information.

As illustrated in Scheme 5, treatment of the labile bis(acetonitrile) complexes (S_C)-**6** and (S_C)-**7** with stoichiometric quantities of DMPP leads to the formation of (S_C)-**6a** and (S_C)-**7a** in high yield. Complexes (S_C)-**6a** and (S_C)-**7a** have also been synthesized previously by a different method.[12b] In all cases, the ^1H, $^{31}P\{^1H\}$, and $^{13}C\{^1H\}$ NMR spectroscopic data for complexes (S_C)-**6a** and (S_C)-**7a** were consistent with those previously reported.

Treatment of a dichloromethane solution of (S_C)-**6a** with a stoichiometric amount of DMAA produced two diastereomeric Diels–Alder cycloadducts, (S_C)-**8a** and (S_C)-**8b**, as evidenced by $^{31}P\{^1H\}$ NMR spectroscopy

Scheme 6



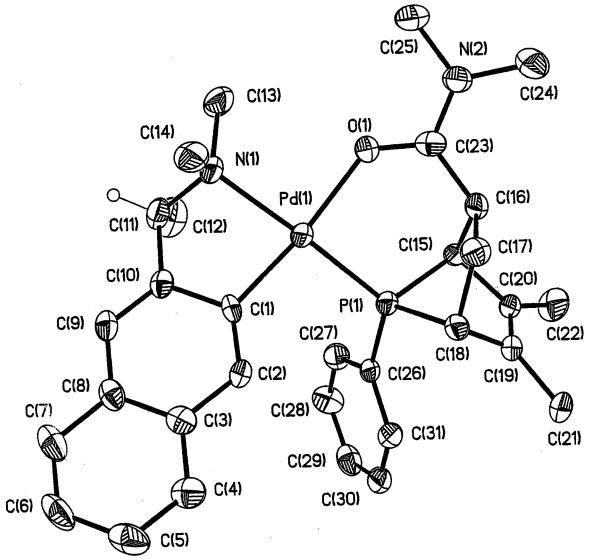
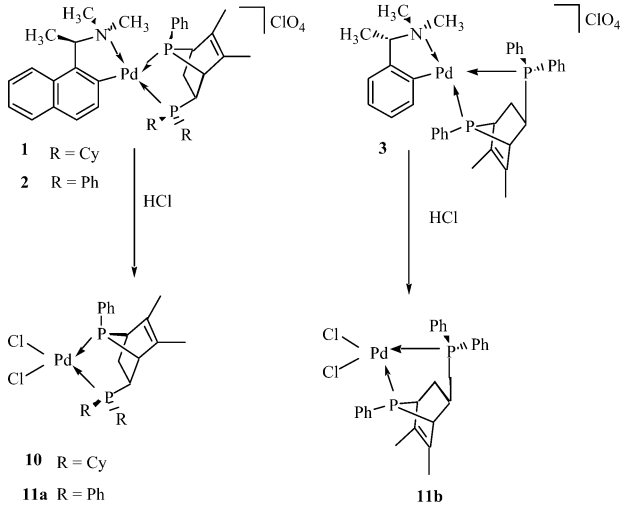


Figure 3. Structural drawing of **8b** showing the atom-numbering scheme (30% probability thermal ellipsoids). Hydrogen atoms are omitted for clarity.

(Scheme 6). Diastereomers (S_C)-**9a** and (S_C)-**9b** were also prepared by the same methodology from (S_C)-**7a**. The major diastereomer formed from (S_C)-**6a**, (S_C)-**8b**, has been isolated as a yellow crystalline solid, whereas the minor diastereomer (S_C)-**8a** is obtained as an off-white solid by fractional crystallization. The $^{31}P\{^1H\}$ NMR spectrum of the crystallized material for these two compounds each exhibited a single resonance at $\delta =$ 112.97 and 112.06 ppm, respectively. The molecular structures and absolute configurations (*S* at P, C(15) and *R* at C(16) and C(18)) of the major diastereomer (S_C)-**8b** and (*R* at P, C(15) and *S* at C(16), C(18)) of the minor diastereomer (S_C)-**8a** have been confirmed by X-ray crystallography. The crystal structure of the cation of (S_C)-**8b** is shown in Figure 3, and that of (S_C)-**8a** is given in the Supporting Information. Crystallographic data for (S_C)-**8a** and (S_C)-**8b** are given in Table 1, and selected bond distances and angles in Table 2.

Scheme 7



The absolute configurations for the four stereogenic centers *R* at P(1), C(18) and *S* at C(15) and C(16) for (S_C)-**8a** and *S* at P(1), C(18) and *R* at C(15) and C(16) for (S_C)-**8b**, respectively, were assigned from the crystal structures.

Removal of the Chiral Auxiliary. As illustrated in Scheme 7 the chiral auxiliary amine can be removed from (R_C)-**1**, (S_C)-**2**, and (S_C)-**3** using concentrated hydrochloric acid in dichloromethane/acetone solvents. The synthesis and characterization of **11a** and **11b** have been described previously, and that of (R_P)-**10** is described in this report. X-ray quality crystals of (R_P)-**10** were grown by slow evaporation of methanol/ether solvent mixtures. The neutral dichloro complex (R_P)-**10** was obtained as a pale yellow crystal in 70% isolated yield. Crystallographic data are given in Table 1. A view of the complex and selected bond distances and angles are shown in Figure 4. The X-ray analysis established the absolute configuration of the four stereogenic centers as *S* at P(2) and C(2) and *R* at C(1) and C(4). The geometry at palladium is slightly distorted square planar, and the angles at palladium range from

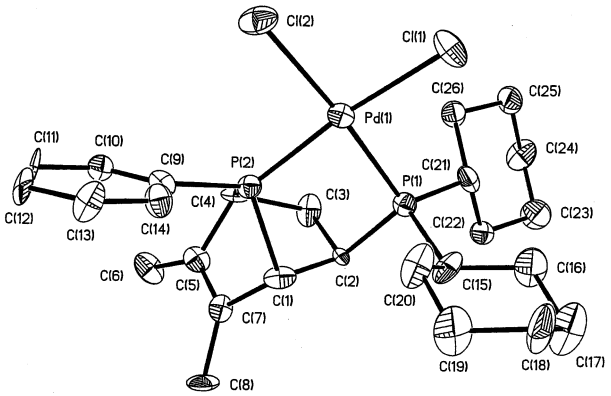
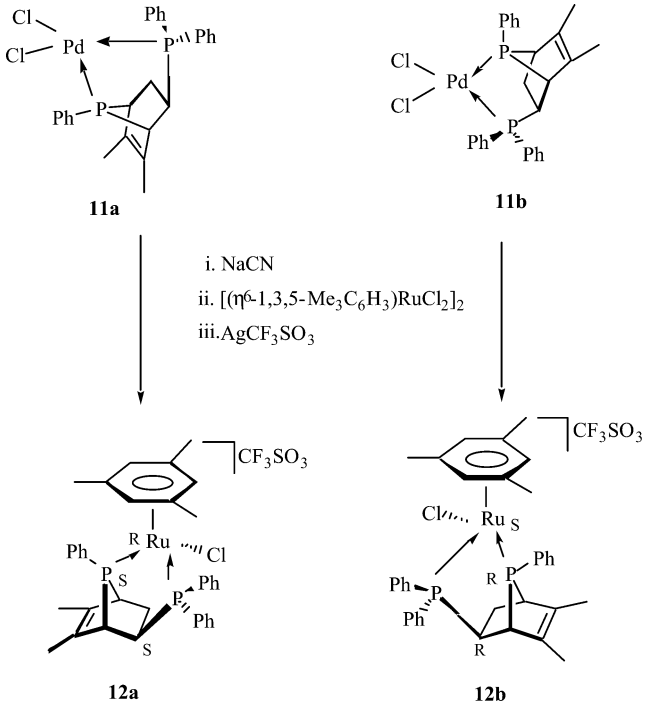
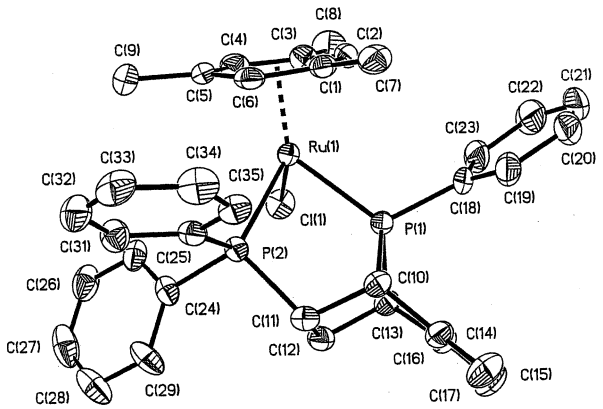


Figure 4. Structural drawing of **10** showing the atom-numbering scheme (30% probability thermal ellipsoids). Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and bond angles (deg): Pd−P(1), 2.243(5); Pd−P(2), 2.236(5); Pd−Cl(1), 2.372(5); Pd−Cl(2), 2.372(5); P(1)−Pd−P(2), 83.40(17); P(1)−Pd−Cl(1), 90.29(19); P(2)−Pd−Cl(1), 173.4(2); P(1)−Pd−Cl(2), 174.4(2); P(2)−Pd−Cl(2), 91.17(19); Cl(1)−Pd−Cl(2), 95.2(2).

Scheme 8



83.40(17)° to 95.2(2)°, the smallest of these angles being associated with the bite of the dicyclohexylphosphino-phosphanorbornene ligand. The two Pd−Cl bonds (2.372-(5) Å) are exactly the same, but the Pd−P bond lengths (Pd−P(1), 2.243(5) Å; Pd−P(2), 2.236(5) Å) slightly differ, with the Pd−P(1) being the longer bond, implying a possible steric effect due to the two bulky cyclohexyl rings. The $^{31}P\{^1H\}$ NMR spectrum of the dichloro complex (R_P)-**10** exhibited a pair of singlets at 125.30 and 58.57 ppm corresponding to the bridgehead phosphorus and PCy_2 group, respectively. For these types of complexes, usually there is a small P−P coupling in the range 0−7.0 Hz.[13b] However, for the dichloro complex (R_P)-**10** no P−P coupling was observed. The ^1H and $^{13}C\{^1H\}$ chemical shift assignments for (R_P)-**10** have been accomplished by COSY, APT, $^1H\{^{31}P\}$, and HETCOR NMR spectra.



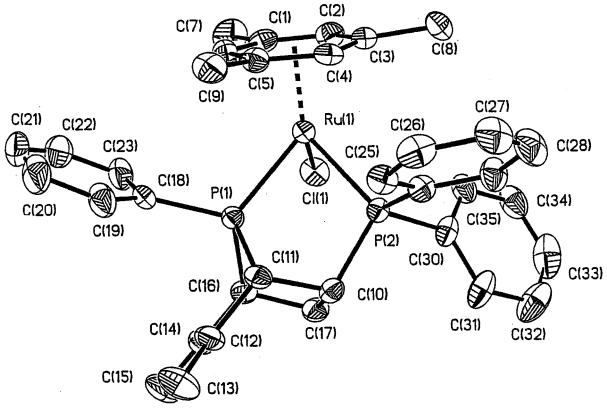


Figure 5. Structural drawings of the cations of **12a** and **12b** showing the atom-numbering scheme (30% probability thermal ellipsoids). Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and bond angles (deg) for **12a**: Ru−P(1), 2.2852(19); Ru−P(2), 2.326(2); Ru−Cl, 2.4038-(16); Ru−C(1), 2.295(7); Ru−C(2), 2.287(8); Ru−C(3), 2.301-(9); Ru−C(4), 2.202(7); Ru−C(5), 2.250(7); Ru−C(6), 2.283-(8); P(1)−Ru−Cl, 86.27(7); P(2)−Ru−Cl, 93.12(7); P(1)−Ru−P(2), 79.66(7). Selected bond lengths (Å) and bond angles (deg) for **12b**: Ru−P(1), 2.287(7); Ru−P(2), 2.3266-(19); Ru−Cl, 2.4081(14); Ru−C(1), 2.257(6); Ru−C(2), 2.281(7); Ru−C(3), 2.287(7); Ru−C(4), 2.281(7); Ru−C(5), 2.322(7); Ru−C(6), 2.203(6); P(1)−Ru−Cl, 86.38(7); P(2)−Ru−Cl, 93.25(7); P(1)−Ru−P(2), 79.64(7). The differences in metrical parameters for **12a** and **12b** are not statistically significant.

Synthesis of 12a and 12b. Release of the *P*-chiral phosphine ligands was achieved by treatment of a dichloromethane solution of **11a** and **11b** with saturated aqueous sodium cyanide. Since these enantiomerically pure phosphines are extremely air-sensitive and prone to oxidation, they were not isolated. Instead, solutions of these ligands were reacted directly with [(η^6-1,3,5-$Me_3C_6H_3$)$RuCl_2$]$_2$ in the presence of $AgCF_3SO_3$ to form [(η^6-1,3,5-$Me_3C_6H_3$)Ru(P∼P)Cl]CF_3SO_3 complexes, chiral at ruthenium (Scheme 8). The diastereoselectivity in the formation of these complexes was very similar to that found for the racemic complexes.[9a] X-ray quality crystals of **12a** and **12b** were grown by slow diffusion of ether into a nitromethane solution. The crystal structures of **12a** and **12b** and selected bond distances and angles are shown in Figure 5. The absolute configurations of **12a** ($R_{Ru}S_P$) and **12b** ($S_{Ru}R_P$) have been confirmed by

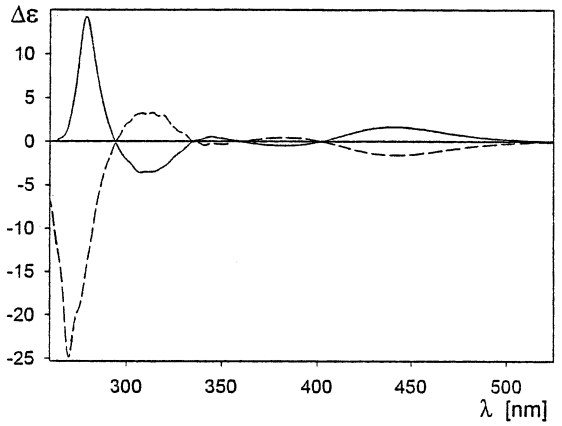


Figure 6. Circular dichroism spectra of **12a** (−) and **12b** (···) in CH_2Cl_2.

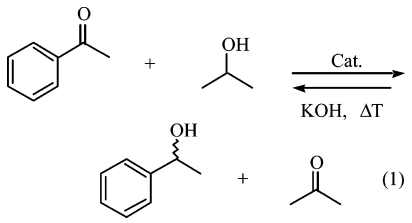
X-ray crystallography. The complexes crystallized as discrete cations and anions with no unusual interionic contacts. The ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectroscopic data are the same as those of the previously reported racemic compounds.[9a]

The circular dichroism (CD) spectra (Figure 6) of the two enantiomers **12a** and **12b** have been measured. Because these two compounds differ in the configuration of the metal stereocenters as well as the other stereogenic centers, their CD spectra are mirror images. For instance the characterstic long-wavelength absorption at 450 nm is positive for **12a** but negative for **12b**, indicative of opposite configurations at the ruthenium center in **12a** and **12b**.

Synthesis of 13. The sterically bulky enantiomerically pure dicyclohexyl disphosphine ligand was liberated from the palladium complex by treating a dichloromethane solution of **10** with saturated aqueous sodium cyanide. The organic layer was separated, dried with anhydrous Na_2SO_4, filtered through Celite, and reacted with $[(\eta^6\text{-}p\text{-cymene})RuCl_2]_2$ in the presence of $AgCF_3SO_3$ to form diastereomeric complexes **13a** and **13b** (Scheme 9), chiral at ruthenium. The diastereoselectivity of this reaction was rather low (**13a**:**13b** = 3.1:1). Similar low diastereoselectivity was observed with the analogous sterically bulky phosphinoarsine bidentate ligand.[11] All attempts to separate the two diastereomers by fractional crystallization or column chromatography were unsuccessful.

Synthesis of 14. The optically pure amidophosphine ligand was liberated from the chiral metal template by treating a dichloromethane solution of (R_c)-**4** with 1,2-bis(diphenylphosphino)ethane (dppe) (Scheme 10). The corresponding optically pure ligand was liberated with the formation of the diphosphine palladium complex. The later was separated from the mixture by crystallization with ethyl acetate. Owing to the extreme air sensitivity of the free amidophosphine ligand, it was not isolated. Instead, it was directly reacted with $[(\eta^6\text{-}p\text{-cymene})RuCl_2]_2$ in the presence of $AgCF_3SO_3$ to form diastereomeric complexes **14a** and **14b** (Scheme 10) with high diastereoselctivity (**14a**:**14b** = 20:3). Unfortunately, efforts to separate the two diastereomers by fractional crystallization or column chromatography were unsuccessful.

Catalytic Investigation. Enantiomerically pure complexes **12a** and **12b** were tested as catalysts for the asymmetric transfer hydrogenation of acetophenone (eq 1) in 2-propanol in the presence of KOH. The two



enantiomeric complexes were found to catalyze the reduction of acetophenone in high yield, although a significant difference in their behavior was noticed. Thus, complex **12a** exhibited higher activity than **12b**. Moreover, the reaction rate with **12a** was slightly higher than that obtained from the catalysts generated from the racemic analogues. [9b] The reaction of the enantiomerically pure **12a** with a substrate-to-catalyst ratio (S/C) = 200 under conditions identical to those described for the racemic analogues proceeded rapidly to give almost quantitatively chiral 1-phenylethanol with an initial turnover frequency (TOF) of 1066 h^{-1} (racemic, 1004 h^{-1}) in the first 10 min. In contrast, the enantiomerically pure **12b** exhibited less activity (TOF, 435 h^{-1}) compared to the racemic analogues (TOF, 1004 h^{-1}) for the reduction of acetophenone with a S/C = 200 under identical conditions. However, the enatiomerically pure catalysts gave rather low asymmetric induction for the asymmetric transfer hydrogenation of acetophenone. The enantiomeric excess (ee) of the product alcohol was found to be 10% in favor of the *S*-absolute configuration. In our previous report[9b] we proposed that the mechanism of the catalytic reaction involves coordination of the ketonic substrate as part of the catalytic cycle. In this context, coordination of the substrate forms diastereomeric complexes in solution. These diastereomeric complexes are likely in a rapid dynamic equilibrium during the reaction cycle and have very similar thermodynamic stabilities (Scheme 11).

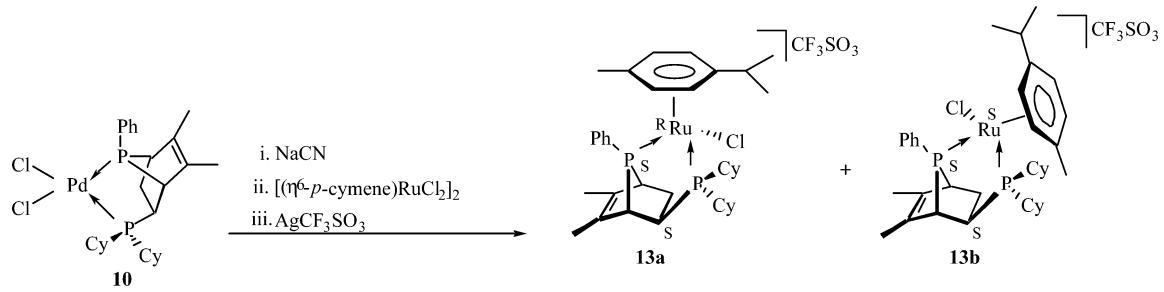
Hence, the poor asymmetric induction exhibited by these catalysts is presumably because of the comparable thermodynamic stabilities of the two diastereomers and their rapid interconversion. Other ruthenium(II) complexes have been reported to catalytically reduce ketones with high enantioselectivities.[14]

Conclusions

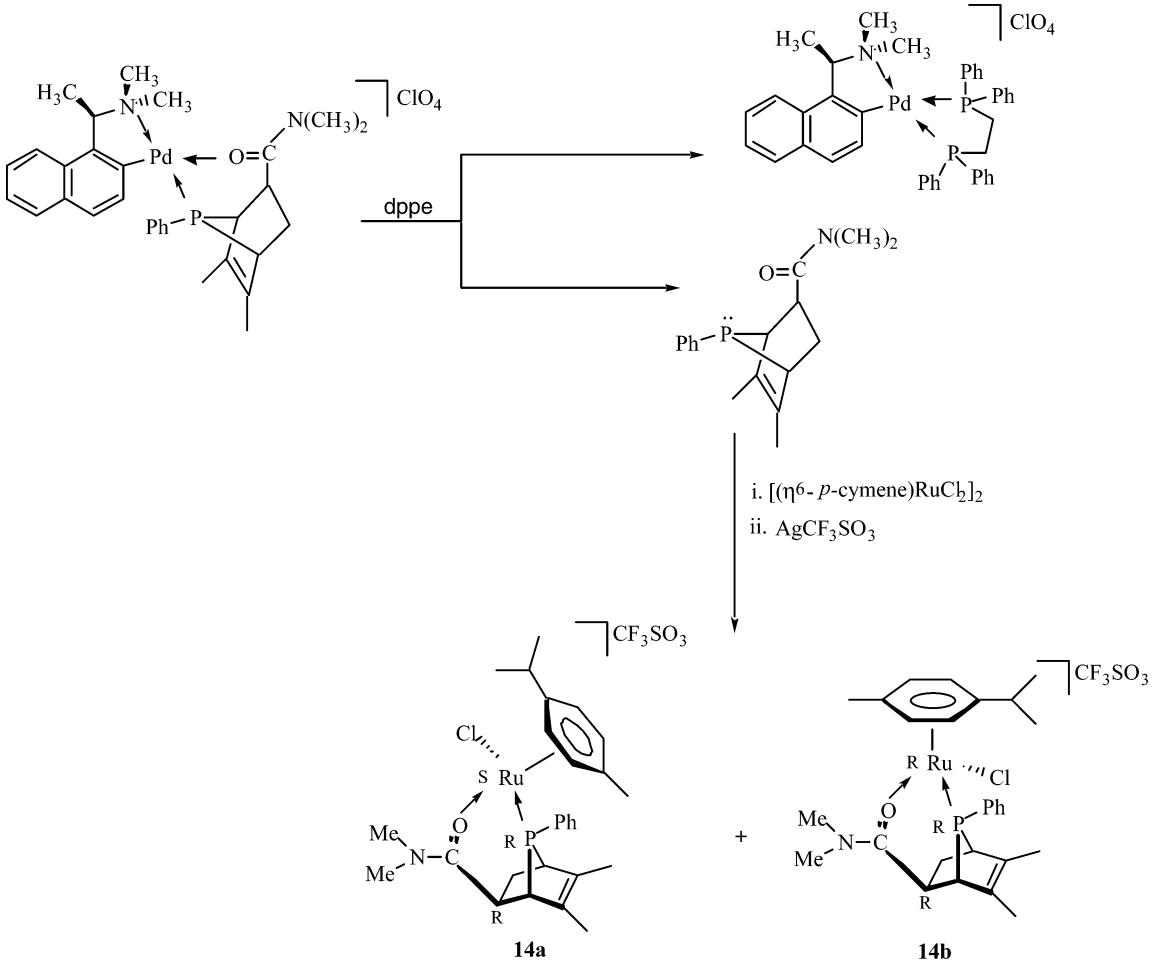
Enantiomerically pure *P*-chiral diphosphine and amidophosphine ligands were prepared by intermolecular Diels−Alder cycloaddition reactions between 3,4-dimethyl-1-phenylphosphole and dicyclohexylvinylphos-

(14) (a) Ohkuma, T.; Koizumi, M.; Muñiz, K.; Hilt, G.; Kabuto, C.; Noyori, R. *J. Am. Chem. Soc.* **2002**, *124*, 6508. (b) Doucet, H.; Ohkuma, T.; Murata, K.; Yokozawa, T.; Kozawa, M.; Kotayama, E.; England, A. F.; Ikariya, T.; Noyori, R. *Angew. Chem., Int. Ed.* **1998**, *37*, 1703. (c) Noyori, R. Ohkuma, T. *Angew. Chem., Int. Ed.* **2001**, *40*, 40. (d) Subongkoj, S.; Lange, S. Chen, W.; Xias, J. *J. Mol. Catal. A: Chem.* **2003**, *196*, 125. (e) Lindner, E.; Ghanem. A.; Warad, I.; Eichele, K.; Mayer, H. A.; Volker, S. *Tetrahedron Asymmetry* **2003**, *14*, 1045. (f) Sturm, T.; Weissensteiner, W.; Spindler, F. *Adv. Synth. Catal.* **2003**, *345*, 160. (g) Chaplin, D.; Harrison, P.; Henschke, J. P.; Lennon, I. C.; Meek, G.; Moran, P.; Pilkington, C. J.; Ramsden, J. A.; Watkins, S.; Zanotti-Gerosa, A. *Org. Proc. Res. Dev.* **2003**, *7*, 89. (h) Kim, G.-J.; Kim, S.-H.; Chong, P.-H.; Kwon, M.-A. *Tetrahedron, Lett.* **2002**, *43*, 8059. (i) Pastor, I. M.; Vaestilae, P.; Adolfsson, H. *Chem. Commun.* **2002**, 2046. (j) Helmchen, G.; Pfaltz, A. *Acc. Chem. Res.* **2000**, *33*, 336.

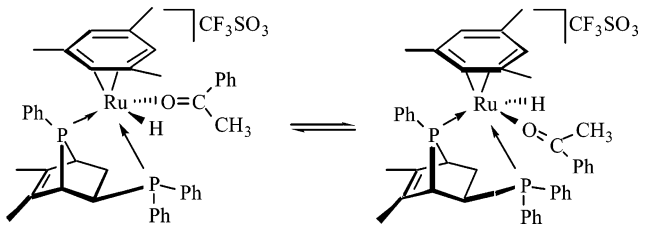
Scheme 9



Scheme 10



Scheme 11



phine, diphenylvinylphosphine, or *N*,*N*-dimethylacrylamide dienophiles using chiral orthopalladated complexes as templates. In each case ligand substitution of the phosphole by the dienophile preceded the cycloaddition reaction. It is clear from all the studies reported to date that the regio- and diastereoselectivities of the metal-promoted intramolecular Diels−Alder cycloadditions between DMPP and a variety of dieneophilic ligands are under thermodynamic control and that intramolecular steric interactions play a dominant role. The *P*-chiral ligands can be liberated from palladium and reacted with [(η^6-arene)$RuCl_2$]$_2$ to produce homo chiral ruthenium(II) complexs. These homo chiral ruthenium(II) complexes were found to catalyze the reduction of acetophenone in 2-propanol in the presence of KOH as a promoter in almost quantitative yield, but gave very poor enantioselectivity.

The relative merits of compounds **A**, **B**, and **C** and the recently reported *N*,*N*-dimethyl-1-(9-phenanthryl)ethylamine analogue as templates for asymmetric Diels−Alder reactions have been repeatedly discussed.[8] For many dienophiles **A** has been found to give the highest enantioselectivities in these reactions. However, for the vinyl phosphines DPVP and DCVP we find very little differences in the enantioselectivities. Thus, for these dienophiles **B** is preferable because the amine

is less expensive, commercially available in quantity, and more easily resolved.

X-ray Data Collection and Processing. Crystals of the complexes, obtained from dichloromethane/ether solvent mixtures for **1**, **5b**, **8a**, and **8b**, acetonitrile/ether for **6** and **7**, methanol/ether for **10**, and nitromethane/ether for **12a** and **12b**, were mounted on glass fibers, coated with epoxy, and placed on a Siemens P4 diffractometer. Intensity data were taken in the ω-mode at 298 K with Mo Kα graphite-monochromated radiation ($\lambda = 0.71073$ Å). Three check reflections monitored every 100 reflections showed random (<2%) variation during the data collections. The data were corrected for Lorentz, polarization effects, and absorption, except for **2**, using an empirical model derived from azimuthal data collections. Scattering factors and corrections for anomalous dispersion were taken from a standard source.[15] Calculations were performed with the Siemens SHELXTL plus version 5.10 software package on a personal computer. The structures were solved by Patterson methods. Anisotropic thermal parameters were assigned to all non-hydrogen atoms. Hydrogen atoms were refined at calculated positions with a riding model in which the C−H vector was fixed at 0.96 Å. Compounds **1**, **8a**, and **10** crystallized as ether, water, and methanol solvates, respectively.

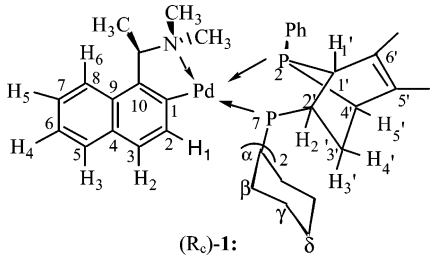
Experimental Section

Reagents and Physical Measurements. All chemicals were reagent grade and were used as received or synthesized as described below. DMPP, [16] DPVP,[17] DCVP, [9d] 1,3,5-trimethylcyclohexa-1,4-diene,[18] $[(\eta^6\text{-arene})RuCl_2]_2$,[19] $[(\eta^6\text{-arene})Ru(DMPP)Cl_2]$,[9a,c] (*S*)-(+)-[(TMBA)PdCl(DMPP)],[11] (*R*)-(−)-[(1TMNA)PdCl(DMPP)],[11] and the chiral (S_C)-**D** and (S_C)-**E** palladium chloride-bridged dimers[12a,20] were synthesized by literature procedures. Elemental analyses were performed by Galbraith Laboratories, Knoxville, TN. Melting points were obtained using a Mel-Temp apparatus and are uncorrected. NMR spectra were recorded on a Varian Unity Plus-500 FT-NMR spectrometer operating at 500 MHz for ^{1}H, 125.7 MHz for ^{13}C, and 202.3 MHz for ^{31}P. Proton and carbon chemical shifts are relative to internal Me_4Si, while phosphorus chemical shifts are relative to external 85% H_3PO_4(aq), with positive values being downfield of the respective reference. Circular dichroism (CD) spectra were recorded on a Jasco J-600 spectrophotometer. Optical rotations were measured on a Perkin-Elmer model 141 polarimeter.

Synthesis of 1−3. To a suspension of 3.0 g (5.64 mmol) of (R_C)-**A** in 60 mL of CH_2Cl_2 was added a solution of 1.3 g (6.2 mmol) of $AgClO_4$ in 2 mL of H_2O. The resulting mixture was stirred in the dark at ambient temperature for 2.5 h and then filtered through Celite to remove AgCl. To the filtrate was added via syringe 1.5 g (6.70 mmol) of $Cy_2PCH{=}CH_2$, and the mixture was stirred at ambient temperature for two weeks. The solvent was removed by rotary evaporation, and the residue was dissolved in a minimum amount of CH_2Cl_2. Slow addition of ether gave a pale yellow microcrystalline solid, which was shown by ^{31}P{^{1}H} NMR spectroscopy to be a single diastereomer of (R_C)-**1**. Complexes (R_C)-**2**[8b] and (S_C)-**3**[8a] were also prepared according to this procedure from (R_C)-**A** and (S_C)-**B**, respectively.

The ^{1}H, ^{13}C{^{1}H}, and ^{31}P{^{1}H} NMR spectroscopic data for (R_C)-**2** and (R_C)-**3** are the same as those previously reported.[8a,b]

Compound (R_C)-1: yield 2.4 g (52%); mp 213-215 °C; $[\alpha]_D$ −108.9° (*c* 1.0, CH_2Cl_2). Anal. Calcd For $C_{40}H_{54}ClNO_4P_2Pd$: C, 58.83; H, 6.66; Cl, 4.34. Found: C, 58.62; H, 6.73; Cl, 4.10. ^{1}H



(R_c)-**1:**

NMR (499.819 MHz, $CDCl_3$, 25 °C): δ 7.78 (dd, $^3J(H_3H_4)$ = 7.5 Hz, $^4J(H_3H_5)$ = 2.0 Hz, 1H, H_3), 7.68 (dd, $^3J(H_5H_6)$ = 7.5 Hz, $^4J(H_4H_6)$ = 1.3 Hz, 1H, H_6), 7.55 (d, $^3J(H_1H_2)$ = 8.2 Hz, 1H, H_2), 7.50 (m, 5H, $H_{o,m,p}$), 7.41 (ddd, $^3J(H_5H_6)$ = 7.5 Hz, $^3J(H_4H_5)$ = 6.8 Hz, $^4J(H_3H_5)$ = 2.0 Hz,. 1H, H_5), 7.38 (ddd, $^3J(H_3H_4)$ = 7.5 Hz, $^3J(H_4H_5)$ = 6.8 Hz, $^4J(H_4H_6)$ = 1.3 Hz, 1H, H_4), 7.34 (ddd, $^3J(H_1H_2)$ = 8.2 Hz, $^4J(PH)$ = 6.0 Hz, $^4J(PH)$ = 4.0 Hz, 1H, H_1), 4.32 (apparent quin, $^3J(HH)$ = $^4J(PH)$ = 6.0 Hz, 1H, CH), 3.70 (bs, 1H, H_5), 3.11 (bs, 1H, H_1), 2.75 (dddd, $^3J(PH)$ = 30.0 Hz, $^2J(PH)$ = 10.0 Hz, $^3J(H_{2'}H_{4'})$ = 9.8 Hz, $^3J(H_{1'}H_{2'})$ = 2.0 Hz, 1H, H_2), 2.70 (m, 1H, H_α), 2.55 (m, 1H, H_α), 2.51 (d, $^4J(PH)$ = 3.0 Hz, 3H, NCH_3), 2.36 (d, $^4J(PH)$ = 1.5 Hz, 3H, NCH_3), 2.26 (m, 1H, $H_{3'}$), 2.0 (m, 2H, H_β), 1.82 (d, $^3J(HH)$ = 6.0 Hz, 3H, $CHCH_3$), 1.81 (m, 2H, H_β), 1.80 (s, 3H, $CH_3(C_6)$), 1.70 (m, 1H, $H_{4'}$), 1.55 (m, 6H, $H_{\beta,\gamma}$), 1.38 (m, 6H, $H_{\beta,\gamma}$), 1.07 (m, 2H, H_δ), 0.9 (m, 2H, H_δ). ^{31}P{^{1}H} NMR (202.326 MHz, $CDCl_3$, 25 °C): δ 118.40 (d, $^2J(PP)$ = 37.4 Hz, 1P, P_7), 70.37 (d, $^2J(PP)$ = 37.4 Hz, 1P, P_2). ^{13}C{^{1}H} NMR (125.690 MHz, $CDCl_3$, 25 °C): δ 158.27 (dd, $^2J(PC)$ = 111.9 Hz, $^2J(PC)$ = 2.6 Hz, C_1), 150.90 (d, $^2J(PC)$ = 1.5 Hz, $C_{5'}$), 136.39 (apparent t, $^2J(PC)$ = $^3J(PC)$ = 2.0 Hz, $C_{6'}$), 134.84 (dd, $^3J(PC)$ = 8.3 Hz, $^3J(PC)$ = 3.0 Hz, C_2), 132.24 (d, $^2J(PC)$ = 10.2 Hz, C_o), 131.83 (s, C_9), 131.36 (s, C_p), 129.37 (d, $^3J(PC)$ = 8.9 Hz, C_m), 129.13 (d, $^3J(PC)$ = 6.5 Hz, C_{10}), 128.65 (s, C_5), 127.84 (d $^5J(PC)$ = 12.7 Hz, C_4), 126.84 (d, $^1J(PC)$ = 22.6 Hz, C_i), 126.14 (s, C_6), 126.00 (dd, $^4J(PC)$ = 7.5 Hz, $^4J(PC)$ = 4.5 Hz, C_3), 124.74 (s, C_7), 123.55 (s, C_8), 75.21 (dd, $^3J(PC)$ = 3.4 Hz, $^3J(PC)$ = 2.3 Hz, CH), 55.14 (dd, $^1J(PC)$ = 29.4 Hz, $^3J(PC)$ = 8.2 Hz, $C_{1'}$), 51.29 (d, $^3J(PC)$ = 2.3 Hz, NCH_3), 50.64 (d, $^3J(PC)$ = 5.2 Hz, NCH_3), 46.61 (d, $^1J(PC)$ = 20.7 Hz, $C_{4'}$), 38.18 (d, $^1J(PC)$ = 21.9 Hz, C_α), 37.24 (d, $^1J(PC)$ = 19.4 Hz, C_α), 35.52 (d, $^2J(PC)$ = 4.4 Hz, C_β), 32.84 (s, C_β), 31.11 (dd, $^2J(PC)$ = 19.9 Hz, $^2J(PC)$ = 2.1 Hz, $C_{3'}$), 30.85 (d, $^2J(PC)$ = 5.7 Hz, C_β), 30.66 (d, $^2J(PC)$ = 4.7 Hz, C_β), 29.93 (dd, $^1J(PC)$ = 40.0 Hz, $^2J(PC)$ = 25.9 Hz, $C_{2'}$), 28.15 (d, $^3J(PC)$ = 14.1 Hz, C_γ), 27.75 (d, $^3J(PC)$ = 13.8 Hz, C_γ), 27.17 (s, $_\gamma$), 27.10 (s, C_γ), 25.70 (s, C_δ), 25.47 (s, C_δ), 24.57 (s, $CHCH_3$), 14.56 (d, $^3J(PC)$ = 1.9 Hz, $CH_3(C_6)$), 13.41 (d, $^3J(PC)$ = 2.3 Hz, $CH_3(C_5)$).

Synthesis of (R_C)-4 and (S_C)-5. Complexes (R_C)-**4** and (S_C)-**5** were prepared by the same general method as follows. To a suspension of 3.0 g (5.64 mmol) of (R_C)-**A** or 3.0 g (6.24 mmol) of (S_C)-**B** in 60 mL of CH_2Cl_2 was added a solution of 1.3 g of $AgClO_4$ in 2 mL of H_2O. The resulting mixture was stirred in the dark at ambient temperature for 2.5 h under nitrogen and then filtered through Celite to remove AgCl. To the filtrate was added 0.8 g (8.10 mmol) of $(CH_3)_2NC(O)CH{=}CH_2$ (DMAA), and the mixture was stirred at ambient temperature for two weeks. The solvent was removed by rotary evaporation, and the residue was dissolved in a minimum amount of CH_2Cl_2 and layered with ether. This afforded 3.0 g (80%) of (R_C)-**4** as a single diastereomer and 2.4 g (70%) of (S_c)-**5** as a mixture of two diastereomers, (S_C)-**5a** and (S_C)-**5b**,

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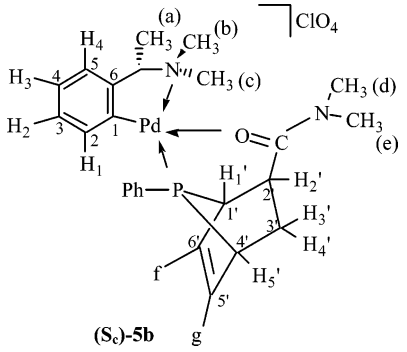
in a 9:1 ratio as evidenced by $^{31}P\{^1H\}$ NMR spectroscopy. The ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectroscopic data for (R_C)-**4** are the same as those previously reported.[8c]

Compound (S_C)-5b: mp 165−168 °C; $[\alpha]_D$ +143° (*c* 1.0, CH_2Cl_2). Anal. Calcd For $C_{27}H_{36}ClN_2O_5PPd$: C, 50.56; H, 5.66; Cl, 5.53. Found: C, 50.36; H, 5.56; Cl, 5.33. ^1H NMR (499.822

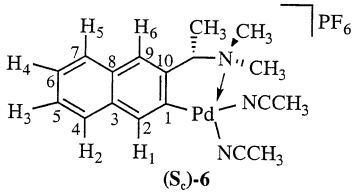


(S$_C$)-5b

MHz, acetone-d_6, 25 °C): δ 7.80 (m, 2H, H_o), 7.41 (m, 3H, $H_{m,p}$), 6.94 (dd, $^3J(H_3H_4) = 7.5$ Hz, $^4J(H_2H_4) = 1.5$ Hz, 1H, H_4), 6.80 (apparent td, $^3J(H_3H_4) = {}^3J(H_2H_3) = 7.5$ Hz, $^4J(H_1H_3) = 1.0$ Hz, 1H, H_3), 6.72 (ddd, $^3J(H_1H_2) = 7.5$ Hz, $^4J(PH) = 6.5$ Hz, $^4J(H_1H_3) = 1.0$ Hz, 1H, H_1), 6.54 (apparent td, $^3J(H_1H_2) = {}^3J(H_2H_3) = 7.5$ Hz, $^4J(H_2H_4) = 1.5$ Hz, 1H, H_2), 3.85 (apparent quin, $^4J(H_1H_5) = {}^3J(H_3H_5) = {}^3J(H_4H_5) = {}^2J(PH) = 2.0$ Hz, 1H, $H_{5'}$), 3.70 (qd, $^3J(HH) = 6.5$ Hz, $^4J(PH) = 6.0$ Hz, 1H, CH), 3.54 (dddd, $^3J(PH) = 21.0$ Hz, $^3J(H_2H_4) = 10.5$ Hz, $^3J(H_2H_3) = 5.0$ Hz, $^3J(H_1H_2) = 1.5$ Hz, 1H, H_2), 3.38 (s, 3H, NCH_3(d)), 3.22 (s, 3H, NCH_3(e)), 3.19 (apparent dt, $^4J(H_1H_5) = 2.0$ Hz, $^3J(H_1H_2) = {}^2J(PH) = 1.5$ Hz, 1H, H_1), 2.86 (dddd, $^2J(H_3H_4) = 13.5$ Hz, $^3J(H_2H_3) = 5.0$ Hz, $^3J(PH) = 3.0$ Hz, $^3J(H_3H_5) = 2.0$ Hz, 1H, H_3), 2.83 (d, $^4J(PH) = 3.5$ Hz, 3H, NCH_3(b)), 2.66 (d, $^4J(PH) = 1.5$ Hz, 3H, NCH_3(c)), 2.45 (dddd, $^3J(PH) = 36.5$ Hz, $^2J(H_3H_4) = 13.5$ Hz, $^3J(H_2H_4) = 10.5$ Hz, $^3J(H_4H_5) = 2.0$ Hz, 1H, H_4), 1.91 (apparent t, $^4J(HH) = {}^4J(PH) = 1.0$ Hz, 3H, CH_3-(g)), 1.71 (d, $^3J(HH) = 6.5$ Hz, 3H, $CHCH_3$(a)), 1.47 (d, $^4J(HH) = 1.0$ Hz, 3H, CH_3(f)). $^{13}C\{^1H\}$ NMR (125.698 MHz, acetone-d_6, 25 °C): δ 180.07 (s, C═O), 156.11 (d, $^2J(PC) = 1.8$ Hz, C_1), 144.58 (d, $^3J(PC) = 2.0$ Hz, C_6), 138.64 (d, $^3J(PC) = 13.2$ Hz, C_2), 136.47 (d, $^2J(PC) = 1.3$ Hz, $C_{6'}$), 134.77 (s, $C_{5'}$), 134.25 (d, $^2J(PC) = 10.2$ Hz, C_o), 131.70 (d, $^4J(PC) = 2.5$ Hz, C_p), 129.19 (d, $^3J(PC) = 10.3$ Hz, C_m), 128.44 (d, $^1J(PC) = 44.5$ Hz, C_i), 126.63 (d, $^4J(PC) = 5.8$ Hz, C_3), 125.49 (s, C_4), 123.64 (s, C_5), 74.45 (d, $^3J(PC) = 2.9$ Hz, CH), 50.83 (d, $^3J(PC) = 2.6$ Hz, NCH_3(b)), 50.61 (d, $^1J(PC) = 30.8$ Hz, $C_{1'}$), 46.35 (d, $^1J(PC) = 28.9$ Hz, $C_{4'}$), 45.72 (d, $^3J(PC) = 2.1$ Hz, NCH_3(c)), 41.05 (d, $^2J(PC) = 14.6$ Hz, $C_{2'}$), 39.33 (s, NCH_3(d)), 38.29 (s, NCH_3(e)), 32.37 (d, $^2J(PC) = 27.0$ Hz, $C_{3'}$), 24.86 (s, $CHCH_3$(a)), 14.34 (d, $^3J(PC) = 3.0$ Hz, CH_3(g)), 13.92 (d, $^3J(PC) = 2.6$ Hz, CH_3(f)). $^{31}P\{^1H\}$ NMR (202.327 MHz, acetone-d_6, 25 °C): δ 94.47 (s, 1P, P_7).

Synthesis of (S_C)-6 and (S_C)-7. To a stirred solution of 0.8 g (1.18 mmol) of the palladium dimer (S_C)-**D** or (S_C)-**E** in 50 mL of freshly distilled CH_3CN under nitrogen was added 0.6 g (2.36 mmol) of $AgPF_6$. The mixture was stirred magnetically in the dark at ambient temperature for 45 min. The resulting mixture was filtered through a layer of Celite to remove AgCl. The pale yellow filtrate was reduced to ca. 1.5 mL via rotary evaporation, and diethyl ether was added to crystallize (S_C)-**6** as yellow prisms. Yield: 1.1 g (87.5%). Mp: 194−195 °C. $[\alpha]_D$ +11.5° (*c* 0.2, CH_2Cl_2). Anal. Calcd for $C_{18}H_{22}F_6N_3PPd$: C, 40.67; H, 4.14. Found: C, 40.53; H, 4.20.

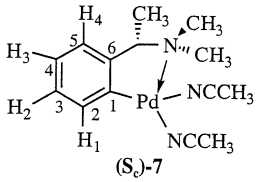
(S_C)-6: ^1H NMR (499.841 MHz, acetone-d_6, 25 °C): δ 7.79 (m, 1H, H_2), 7.75 (m, 1H, H_5), 7.49 (d, $^4J(H_6CH) = 1.0$ Hz, 1H, H_6), 7.48 (s, 1H, H_1), 7.41 (m, 2H, $H_{3,4}$), 4.28 (qd, $^3J(HH) = 6.5$ Hz, $^4J(HH) = 1.0$ Hz, 1H, CH), 2.94 (s, 3H, NCH_3), 2.70 (s, 3H, NCH_3), 2.67 (s, 3H, CH_3CN), 2.20 (s, 3H, CH_3CN), 1.72 (d, $^3J(HH)$ 6.5 Hz, 3H, CCH_3). $^{13}C\{^1H\}$ NMR (125.698 MHz,



(S$_C$)-6

acetone-d_6, 25 °C): δ 152.06 (C_1), 140.27 (C_{10}), 133.22 (C_3), 132.80 (C_8), 128.40 (C_4), 127.95 (C_7), 126.45 (C_5), 126.17 (C_6), 123.37 (CH_3CN), 121.99 ($C_{2,9}$), 119.20 (CH_3CN), 75.82 (CH), 52.35 (NCH_3), 47.28 (NCH_3), 19.14 (CCH_3), 3.25 (CH_3CN), 1.64 (CH_3CN).

(S_C)-7: colorless crystalline solid. Yield: 1.13 g (85%). Mp: 162−164 °C. $[\alpha]_D$ +28.6° (*c* 0.5, CH_2Cl_2). Anal. Calcd for $C_{14}H_{20}F_6N_3PPd$: C, 34.92; H, 4.15. Found: C, 34.85; H, 4.10.



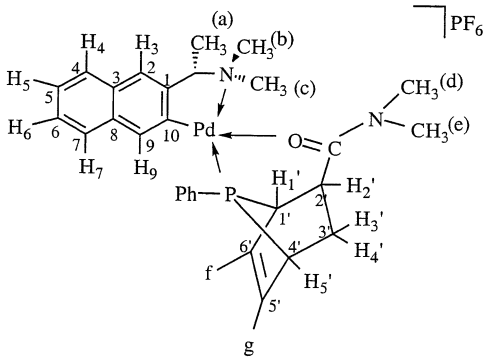
(S$_C$)-7

^1H NMR (499.841 MHz, acetone-d_6, 25 °C): δ 7.06 (apparent td, $^3J(H_2H_3) = {}^3J(H_3H_4) = 7.5$ Hz, $^4J(H_1H_3) = 1.0$ Hz, 1H, H_3), 7.02 (dd, $^3J(H_1H_2) = 7.5$ Hz, $^4J(H_1H_3) = 1.0$ Hz, 1H, H_1), 6.95 (dd, $^3J(H_3H_4) = 7.5$ Hz, $^4J(H_2H_4) = 1.5$ Hz, 1H, H_4), 6.90 (apparent td, $^3J(H_1H_2) = {}^3J(H_2H_3) = 7.5$ Hz, $^4J(_2H_4) = 1.5$ Hz, 1H, H_2), 4.04 (q, $^3J(HH) = 6.5$ Hz, 1H, CH), 2.89 (s, 3H, NCH_3), 2.65 (s, 3H, NCH_3), 2.57 (s, 3H, CH_3CN), 2.26 (s, 3H, CH_3-CN), 1.58 (d, $^3J(HH) = 6.5$ Hz, 3H, CCH_3). $^{13}C\{^1H\}$ NMR (125.698 MHz, acetone-d_6, 25 °C): δ 154.23 (C_1), 142.81 (C_6), 134.22 (C_5), 126.69 (C_3), 126.46 (C_4), 133.62 (C_2), 122.97 (CH_3CN), 120.20 (CH_3CN), 76.30 (CH), 47.53 (NCH_3), 19.95 (CCH_3), 2.94 (CH_3CN), 1.85 (CH_3CN).

Synthesis of (S_C)-6a and (S_C)-7a. To a stirred solution of (S_C)-**6** or (S_C)-**7** 0.6 g in CH_2Cl_2 (50 mL) under nitrogen was added 0.21 mL (1.13 mmol) of 3,4-dimethyl-1-phenylphsphole (DMPP) via syringe. Upon addition of the phosphine, a transparent pale yellow solution was formed. This solution was stirred magnetically for 2 h at ambient temperature. The solution was reduced in volume to ca. 5 mL via rotary evaporation, and *n*-hexane was added to precipitate the product as a pale yellow solid. The precipitate was isolated by filtration, washed with several small portions of hexane/ether (1:1), and air-dried. The solid was recrystallized from acetone/ether (1:2) to afford (S_C)-**6a** as a pale yellow prism in 93.5% yield and (S_C)-**7a** in 90% yield, respectively. The ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectroscopic data are the same as those previously reported.[12b]

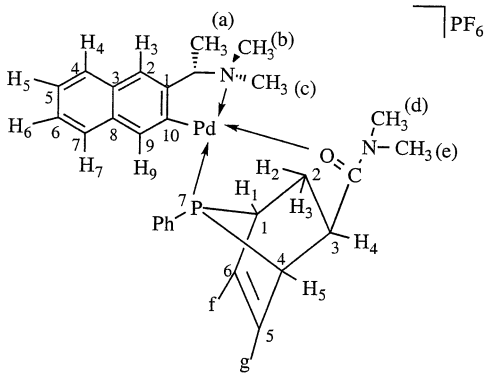
Synthesis of (S_C)-8 and (S_C)-9. Complexes (S_C)-**8** and (S_C)-**9** were prepared by the same general method as follows. To a solution of 3.0 g (5.64 mmol) of (S_C)-**6** or 3.0 g (6.24 mmol) of (S_C)-**7** in 60 mL of CH_2Cl_2 under nitrogen was added 0.8 g (8.10 mmol) of $(CH_3)_2NC(O)CH{=}CH_2$ (DMAA) via syringe, and the mixture was stirred at ambient temperature for 3 days to give a pair of diastereomers, (R_P,S_C)-**8a**, (S_P,S_C)-**8b**, and (R_P,S_C)-**9a** and (S_P,S_C)-**9b**, respectively. Prior to purification, the $^{31}P\{^1H\}$ NMR spectrum of the crude reaction product of (S_C)-**8** in $CDCl_3$ exhibited two sharp singlets at 110.89 and 110.03 ppm in the ratio of 1:2.4. Recrystallization of the mixture from dichloromethane/diethyl ether afforded 26.7% of (S_C)-**8a** (minor) and 31.5% of (S_C)-**8b** (major). (S_C)-**8a**: mp 205−207 °C; $[\alpha]_D$ +43.4° (*c* 0.2, CH_2Cl_2). Anal. Calcd for $C_{31}H_{38}F_6N_2OP_2Pd$,: C, 50.52; H, 5.20. Found: C, 50.30; H, 5.10.

(S_C)-8a: ^1H NMR (499.837 MHz, CD_3NO_2, 25 °C): δ 7.85 (m, 2H, H_o), 7.63 (m, 1H, H_7), 7.45 (s, 1H, H_2), 7.40 (m, 3H, $H_{m,p}$), 7.30 (m, 3H, $H_{4,5,6}$), 7.11 (d, $^4J(PH) = 6.5$ Hz, 1H, H_9), 3.86 (dq, $^3J(HH) = 6.5$ Hz, $^4J(PH) = 6.0$ Hz, 1H, CH), 3.83



(S_C)-8a

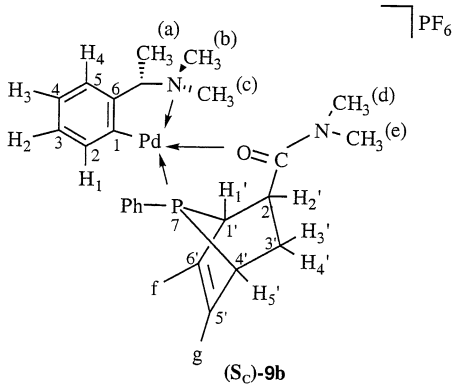
(apparent quin, ^2J(PH) = ^3J(H$_{3'}$H$_{5'}$) = ^3J(H$_{4'}$H$_{5'}$) = ^4J(H$_{1'}$H$_{5'}$) = 2.0 Hz, 1H, H$_{5'}$), 3.47 (dddd, ^3J(PH) = 21.0 Hz, ^3J(H$_{2'}$H$_{4'}$) = 10.0 Hz, ^3J(H$_{2'}$H$_{3'}$) = 5.0 Hz, ^3J(H$_{1'}$H$_{2'}$) = 1.5 Hz, 1H, H$_{2'}$), 3.32 (s, 3H, NCH$_3$(e)), 3.22 (s, 3H, NCH$_3$(d)), 3.15 (apparent dt, ^2J(PH) = 3.0 Hz, ^3J(H$_{1'}$H$_{2'}$) = ^4J(H$_{1'}$H$_{5'}$) = 2.0 Hz, 1H, H$_{1'}$), 2.88 (dddd, ^2J(H$_{3'}$H$_{4'}$) = 13.0 Hz, ^3J(H$_{2'}$H$_{3'}$) = 5.0 Hz, ^3J(H$_{3'}$H$_{5'}$) = 2.0 Hz, ^3J(PH) = 3.0 Hz, 1H, H$_{3'}$), 2.86 (d, ^4J(PH) = 3.5 Hz, 3H, NCH$_3$(b)), 2.68 (d, ^4J(PH) = 1.5 Hz, 3H, NCH$_3$(c)), 2.43 (dddd, ^3J(PH) = 36.0 Hz, ^2J(H$_{3'}$H$_{4'}$) = 13.0 Hz, ^2J(H$_{2'}$H$_{4'}$) = 10.0 Hz, ^3J(H$_{4'}$H$_{5'}$) = 2.0 Hz, 1H, H$_{4'}$), 1.95 (q, ^5J(HH) = 1.5 Hz, 3H, CH$_3$(f)), 1.82 (d, ^3J(HH) = 6.5 Hz, 3H, CH$_3$(a)), 1.52 (q, ^5J(HH) = 1.5 Hz, 3H, CH$_3$(g)). ^{13}C{^{1}H} NMR (125.696 MHz, CD$_3$NO$_2$, 25 °C): δ 179.10 (s, C$_o$), 153.47 (d, ^3J(PC) = 1.8 Hz, C$_{6'}$), 142.26 (d, ^3J(PC) = 2.1 Hz, C$_{5'}$), 136.06 (d, ^2J(PC) = 13.2 Hz, C$_9$), 135.96 (d, ^2J(PC) = 1.0 Hz, C$_{10}$), 133.89 (d, ^4J(PC) = 0.8 Hz, C$_3$), 133.30 (d, ^2J(PC) = 10.10 Hz, C$_o$), 132.27 (d, ^3J(PC) = 5.9 Hz, C$_1$), 131.39 (s, C$_8$), 130.81 (d, ^4J(PC) = 2.3 Hz, C$_p$), 128.30 (d, ^3J(PC) = 10.2 Hz, C$_m$), 127.56 (d, ^1J(PC) = 45.0 Hz, C$_i$), 127.04 (s, C$_7$), 126.23 (s, C$_6$), 125.21 (s, C$_5$), 124.95 (s, C$_4$), 120.58 (s, C$_2$), 73.27 (d, ^4J(PC) = 2.9 Hz, NCH), 49.63 (d, ^3J(PC) = 11.8 Hz, NCH$_3$), 49.60 (d, ^1J(PC) =21.6 Hz, C$_i$), 45.61 (d, ^1J(PC) = 29.2 Hz, C$_{4'}$), 44.49 (d, ^3J(PC) = 1.9 Hz, NCH$_3$), 40.20 (d, ^2J(PC) = 14.7 Hz, C$_{2'}$), 38.04 (s, NCH$_3$), 37.13 (d, ^3J(PC) = 6.8 Hz, NCH$_3$), 31.27 (d, ^2J(PC) = 27.0 Hz, C$_{3'}$), 22.69 (s, CH$_3$), 12.99 (d, ^3J(PC) = 3.1 Hz, CH$_3$), 12.46 (d, ^3J(PC) = 2.6 Hz, CH$_3$). ^{31}P{^{1}H} NMR (202.333 MHz, CD$_3$NO$_2$, 25 °C): 112.06 (s, P$_7$), −142.14 (sept, ^1J(PF) = 707 Hz, PF$_6^-$).



(S_C)-8b

(S_C)-8b: mp 196−198 °C; [α]$_D$ +29.5° (*c* 0.2, CH$_2$Cl$_2$). Anal. Calcd for C$_{31}$H$_{38}$F$_6$N$_2$OP$_2$Pd: C, 50.52; H, 5.20. Found: C, 50.30; H, 5.10. ^{1}H NMR (499.839 MHz, D$_2$O, 25 °C): δ 7.84 (m, 2H, H$_o$), 7.64 (m, 1H, H$_7$), 7.45 (m, 3H, H$_{m,p}$), 7.36 (s, 1H, H$_2$), 7.30 (m, 3H, H$_{4,5,6}$), 6.96 (d, ^4J(PH) = 6.5 Hz, 1H, H$_9$), 4.44 (qt, ^3J(HH) = 6.5 Hz, ^4J(PH) = 6.0 Hz, 1H, CH), 3.81 (apparent quin, ^2J(PH) = ^3J(H$_{3'}$H$_{5'}$) = ^3J(H$_{4'}$H$_{5'}$) = ^4J(H$_{1'}$H$_{5'}$) = 1.5 Hz, 1H, H$_{5'}$), 3.45 (dddd, ^3J(PH) = 21.0 Hz, ^3J(H$_{2'}$H$_{4'}$) = 10.5 Hz, ^3J(H$_{2'}$H$_{3'}$) = 5.0 Hz, ^3J(H$_{1'}$H$_{2'}$) = 1.0 Hz, 1H, H$_{2'}$), 3.44 (dd, ^4J(H$_{1'}$H$_{5'}$) = 1.5 Hz, ^3J(H$_{1'}$H$_{2'}$) = 1.0 Hz, 1H, H$_{1'}$), 3.43 (s, 3H, NCH$_3$(e)), 3.42 (s, 3H, NCH$_3$(d)), 3.41 (s, 3H, NCH$_3$(c)), 3.40 (s, 3H, NCH$_3$(b)), 3.15 (apparent dt, ^3J(H$_{2'}$H$_{3'}$) = 5.0 Hz, ^3J(H$_{3'}$H$_{5'}$) = ^3J(PH) = 1.5 Hz, 1H, H$_{3'}$), 2.45 (dddd, ^3J(PH) = 36.0 Hz, ^2J(H$_{3'}$H$_{4'}$) = 13.0 Hz, ^2J(H$_{2'}$H$_{4'}$) = 10.5 Hz, ^3J(H$_{4'}$H$_{5'}$) = 2.0 Hz, 1H, H$_{4'}$), 1.91 (s, 3H, CH$_3$(f)), 1.63 (d, ^3J(HH) = 6.5 Hz, 3H, CH$_3$(a)), 1.52 (s, 3H, CH$_3$(g)). ^{13}C{^{1}H} NMR (125.696 MHz, D$_2$O, 25 °C): δ 179.06 (s, C=O), 153.47 (d, ^3J(PC) = 1.4 Hz, C$_{6'}$), 151.55 (d, ^3J(PC) = 1.8 Hz, C$_{5'}$), 136.11 (d, ^2J(PC) = 1.0 Hz, C$_{10}$), 135.36 (d, ^2J(PC) = 13.3 Hz, C$_9$), 134.15 (s, C$_3$), 133.39 (d, ^2J(PC) = 9.8 Hz, C$_o$), 132.33 (d, ^3J(PC) = 5.8 Hz, C$_1$), 131.34 (s, C$_8$), 130.94 (d, ^4J(PC) = 2.5 Hz, C$_p$), 128.41 (d, ^3J(PC) = 10.2 Hz, C$_m$), 127.57 (d, ^1J(PC) = 43.36 Hz, C$_i$), 127.24 (s, C$_7$), 126.22 (s, C$_6$), 125.38 (s, C$_5$), 124.945 (s, C$_4$), 121.54 (s, C$_2$), 71.28 (d, ^4J(PC) = 2.8 Hz, NCH), 49.48 (d, ^1J(PC) = 30.3 Hz, C$_{1'}$), 49.52 (d, ^3J(PC) = 2.0 Hz, NCH$_3$(b)), 47.08 (d, ^3J(PC) = 2.3 Hz, NCH$_3$(c)), 45.89 (d, ^1J(PC) = 29.3 Hz, C$_{4'}$), 40.21 (d, ^2J(PC) = 14.7 Hz, C$_{2'}$), 38.09 (s, NCH$_3$(d)), 37.16 (s, NCH$_3$(e)), 31.34 (d, ^2J(PC) = 26.5 Hz, C$_{3'}$), 14.29 (s, CH$_3$(a)), 12.96 (d, ^3J(PC) = 2.9 Hz, CH$_3$(f)), 12.46 (d, ^3J(PC) = 2.6 Hz, CH$_3$)(g)). ^{31}P{^{1}H} NMR (202.333 MHz, D$_2$O, 25 °C): 112.97 (s, P$_7$), −142.14 (sept, ^1J(PF) = 707 Hz, PF$_6^-$).

(S_C)-9b. Prior to purification, the ^{31}P{^{1}H} NMR spectrum of the crude reaction product of (S_C)-**9** in CDCl$_3$ exhibited two sharp singlets at 110.63 and 109.55 ppm in the ratio of 1:3. Recrystallization of the mixture from dichloromethane/diethyl ether afforded 45% of (S_C)-**9b** (major): mp 205−207 °C; [α]$_D$ +43.4° (*c* 0.2, CH$_2$Cl$_2$). Anal. Calcd for C$_{31}$H$_{38}$F$_6$N$_2$OP$_2$Pd,: C, 50.52; H, 5.20. Found: C, 50.30; H, 5.10. Anal. Calcd for

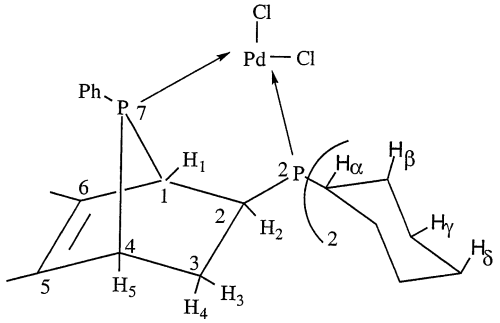


(S_C)-9b

C$_{25}$H$_{30}$F$_6$N$_2$OP$_2$Pd: C, 45.71; H, 4.60. Found: C, 45.51; H, 4.45. ^{1}H NMR (499.845 MHz, CdCl$_3$, 25 °C): δ 7.55 (m, 2H, H$_o$), 7.40 (m, 2H, H$_m$), 7.32 (m, 1H, H$_p$), 6.87 (dd, ^3J(H$_3$H$_4$) = 7.0 Hz, ^4J(H$_2$H$_4$) = 1.5 Hz, 1H, H$_4$), 6.82 (apparent td, ^3J(H$_2$H$_3$) = ^3J(H$_3$H$_4$) = 7.0 Hz, ^4J(H$_1$H$_3$) = 1.5 Hz, 1H, H$_3$), 6.53 (apparent td, ^3J(H$_1$H$_2$) = ^3J(H$_2$H$_3$) = 7.0 Hz, 4(J(H2H4) = 1.5 Hz, 1H, H2), 6.43 (apparent td, ^3J(H$_1$H$_2$) = ^4J(PH) = 7.0 Hz, ^4J(H$_1$H$_3$) = 1.5 Hz, 1H, H$_1$), 3.58 (qd, ^3J(HH) = 7.0 Hz, ^4J(PH) = 5.0 Hz, 1H, CH), 3.46 (apparent quin, ^2J(PH) = ^3J(H$_{3'}$H$_{5'}$) = ^3J(H$_{4'}$H$_{5'}$) = ^4J(H$_{1'}$H$_{5'}$) = 2.0 Hz, 1H, H$_{5'}$), 3.29 (s, 3H, NCH$_3$-(e)), 3.24 (dddd, ^3J(PH) = 21.0 Hz, ^3J(H$_{2'}$H$_{4'}$) = 10.0 Hz, ^3J(H$_{2'}$H$_{3'}$) = 5.5 Hz, ^3J(H$_{1'}$H$_{2'}$) = 2.0 Hz, 1H, H$_{2'}$), 3.15 (s, 3H, NCH$_3$(d)), 3.00 (apparent td, ^2J(PH) = ^3J(H$_{1'}$H$_{2'}$) = ^4J(H$_{1'}$H$_{5'}$) = 2.0 Hz, 1H, H$_{1'}$), 2.82 (m, 1H, H$_{3'}$), 2.73 (d, ^4J(PH) = 3.5 Hz, CH$_3$(b)), 2.64 s, 3H, CH$_3$(c)), 2.30 (dddd, ^3J(PH) = 36.0 Hz, ^2J(H$_{3'}$H$_{4'}$) = 12.5 Hz, ^2J(H$_{2'}$H$_{4'}$) = 10.0 Hz, ^3J(H$_{4'}$H$_{5'}$) = 1.5 Hz, 1H, H$_{4'}$), 1.87 (d, ^5J(HH) = 1.0 Hz, 3H, CH$_3$(f)), 1.70 (d, ^3J(HH) = 6.5 Hz, 3H, CH$_3$(a)), 1.52 (s, 3H, CH$_3$(g)). ^{13}C{^{1}H} NMR (125.696 MHz, CDCl$_3$, 25 °C): δ 178.39 (s, C=O), 154.44 (s, C$_{6'}$), 143.01 (s, C$_{5'}$), 137.24 (d, ^3J(PC) = 13.3 Hz, C$_6$), 135.09 (s, C$_1$), 134.31 (s, C$_2$), 133.13 (d, ^2J(PC) = 10.2 Hz, C$_o$), 131.07 (d, ^4J(PC) = 2.5 Hz, C$_p$), 129.51 (s, C$_3$), 128.42 (d, ^3J(PC) = 10.4 Hz, C$_m$), 126.31 (d, ^1J(PC) = 43.8 Hz, C$_i$), 124.83 (s, C$_4$), 122.86 (s, C$_5$), 73.61 (d, ^4J(PC) = 3.0 Hz, CH), 50.50 (s, NCH$_3$-(e)), 50.21 (d, ^1J(PC) = 30.2 Hz, C$_{1'}$), 45.92 (d, ^1J(PC) = 29.0 Hz, C$_{4'}$), 45.15 (s, NCH$_3$(d)), 40.06 (d, ^2J(PC) = 14.7 Hz, C$_{2'}$), 39.01 (s, NCH$_3$(c)), 37.86 (s, NCH$_3$(b)), 31.63 (d, ^2J(PC) = 21.4 Hz, C$_{3'}$), 29.65 (s, CH$_3$(a)), 14.29 (d, ^{3}J)PC) = 3.0 Hz, CH$_3$(f)),

13.67 (d, ^3J(PC) = 2.6 Hz, CH_3(g)). $^{31}P\{^1H\}$ NMR (202.340 MHz, $CDCl_3$, 25 °C): δ 109.20 (s, 1P, P_7), −145.00 (septet, ^1J(PF) = 707.2 Hz, PF_6^-).

Synthesis of 10, 11a, and 11b. To a solution containing 4.0 g of **1**, **2**, or **3** in 100 mL of CH_2Cl_2 was added 12 mL of concentrated HCl and 50 mL of acetone. The mixture was stirred at ambient temperature for 2.5 days. The CH_2Cl_2 layer was separated and the solvent removed by rotary evaporation. The remaining pale yellow solid was washed with water and crystallized by slow evaporation of CH_2Cl_2 solutions to afford pale yellow crystals of **10**, **11a**, and **11b**. The ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectroscopic data for **11a** and **11b** are the same as those previously reported.[8b,13b]



10

10: mp > 220 °C dec; $[\alpha]_D$ +27.2° (*c* 0.2, CH_2Cl_2). Anal. Calcd for $C_{26}H_{38}Cl_2P_2Pd$: C, 52.95; H, 6.49; Cl, 12.02. Found: C, 52.85; H, 6.42; Cl, 11.95. ^1H NMR (499.82 MHz, CD_2Cl_2, 25 °C); δ 7.55 (m, 2H, H_o), 7.52 (m, 1H, H_p), 7.44 (m, 2H, H_m), 3.33 (bs, 1H, H_5), 3.20 (bs, 1H, H_1), 2.73 (m, 2H, H_β), 2.61 (bm, ^3J(PH) = 47.5 Hz, ^2J(PH) 5.0 Hz, 1H, H_2), 2.56 (dtt, ^2J(PH) = 9.0 Hz, $^3J(H_\alpha H_\beta)$ = 12 Hz, $^3J(H_\alpha H_\beta)$ = 3.0 Hz, 1H, H_α), 2.52 (m, ^2J(PH) = 21.5 Hz, $^2J(H_3H_4)$ = 13.5 Hz, 1H, H_3), 2.40 (m, 4H, H_β), 1.90 (m, 5H, H_4, 2H_β, 2H_γ), 1.76 (m, 4H, H_γ), 1.65 (s, 3H, CH_3), 1.57 (m, 2H, H_β), 1.55 (s, 3H, CH_3), 1.42 (m, 4H, H_γ), 1.30 (m, 4H, H_δ). $^{13}C\{^1H\}$ NMR (125.69 MHz, CD_2Cl_2, 25 °C): δ 137.52 (d, ^2J(PC) = 1.9 Hz, C_5), 133.15 (d, ^2J(PC) = 9.3 Hz, C_o), 131.81 (d, ^4J(PC) = 2.8 Hz, C_p), 129.12 (dd, ^2J(PC) = 16.3 Hz, ^3J(PC) = 1.3 Hz, C_6), 128.52 (d, ^3J(PC) = 10.9 Hz, C_m), 125.89 (d, ^1J(PC) = 46.6 Hz, C_i), 55.88 (dd, ^1J(PC) = 35.7 Hz, ^2J(PC) = 11.4 Hz, C_1), 47.05 (d, ^1J(PC) = 30.2 Hz, C_4), 37.51 (d, ^1J(PC) = 21.1 Hz, C_α), 37.17 (d, ^1J(PC) 23.5 Hz, C_α), 32.66 (d, ^2J(PC) = 1.9 Hz, C_β), 32.22 (d, ^2J(PC) = 1.8 Hz, C_β), 31.16 (d, ^2J(PC) = 19.9 Hz, C_3), 31.06 (d, ^2J(PC) = 6.0 Hz, C_β), 30.19 (d, ^2J(PC) = 2.8 Hz, C_β), 28.30 (d, ^3J(PC) = 13.1 Hz, C_γ), 28.14 (d, ^3J(PC) = 11.9 Hz, C_γ), 28.01 (dd, ^1J(PC) = 39.6 Hz, ^2J(PC) = 25.9 Hz, C_2), 27.67 (d, ^3J(PC) = 10.1 Hz, C_γ), 27.47 (d, ^3J(PC) = 10.9 Hz, C_γ), 26.36 (d, ^4J(PC) = 1.4 Hz, C_δ), 26.20 (d, ^4J(PC) = 1.5 Hz, C_δ), 15.11 (dd, ^3J(PC) = 2.9 Hz, ^4J(PC) = 1.3 Hz, CH_3(6)), 13.85 (d, ^3J(PC) = 3.4 Hz, CH_3(6)). $^{31}P\{^1H\}$ NMR (202.326 MHz, CD_2Cl_2, 25 °C): δ 125.35 (s, 1P, P_7), 58.57 (s, 1P, P_2).

Synthesis of 12a, 12b, and 13. To a solution containing 1.0 g of **10, 11a**, or **11b** in 150 mL of CH_2Cl_2 was added a saturated solution of NaCN in 150 mL of H_2O. The mixture was stirred vigorously under nitrogen for 8 h. The CH_2Cl_2 layer was separated, dried over anhydrous Na_2SO_4, and filtered through Celite into a three-neck round-bottom flask containing 0.5 g of $[(\eta^6\text{-}1,3,5\text{-}Me_3C_6H_3)RuCl_2]_2$ or $[(\eta^6\text{-}p\text{-cymene})RuCl_2]_2$, and the mixture was stirred for 4 h at ambient temperature. To this solution was added 0.30 g of $AgCF_3SO_3$, and the mixture was stirred for 8 h. The resulting solution was filtered through Celite to remove AgCl. The orange-colored filtrate was taken to dryness by rotary evaporation. The residue was dissolved in a minimum amount of nitromethane and layered with diethyl ether to afford diastereomerically pure yellow-orange crystals of **12a** and **12b** or mixtures of the diastereomers **13a** and **13b**, which could not be separated by fractional crystallization or column chromatography on silica gel. The diastereomeric mixture of **13a** and **13b** was characterized only by $^{31}P\{^1H\}$ NMR spectroscopy in a ratio **13a**:**13b** = 3.1:1. $^{31}P\{^1H\}$ NMR (202.326 MHz, CD_2Cl_2, 25 °C): major (**13a**), δ 144.48, (d, ^2J(PP) = 44.3 Hz, 1P, P_7), 53.14 (d, ^2J(PP) = 44.3 Hz, 1P, P_2); minor (**13b**), δ 148.12, (d, ^2J(PP) = 54.8 Hz, 1P, P_7), 67.78 (d, ^2J(PP) = 54.8 Hz, 1P, P_2).

The ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectroscopic data for **12a** and **12b** are the same as those previously reported for the racemic compounds. [9b]

12a: yield (85.5%), mp > 244 °C dec, $[\alpha]_D$ +208.0° (*c* 1.0, CH_2Cl_2). CD (molecular elipticity $[\theta]_\lambda$ (deg cm^2 dmol^{-1}): for 1.1 × 10^{-3} M in CH_2Cl_2 (at 25 °C) $[\theta]_{450}$ = +4950, $[\theta]_{382}$ = −1650, for 1.1 × 10^{-4}, $[\theta]_{345}$ = +1980, $[\theta]_{307}$ = −11880, $[\theta]_{279}$ = +46860.

12b: yield (75.7%), mp > 246 °C dec, $[\alpha]_D$ −220.2° (*c* 1.0, CH_2Cl_2). CD (molecular elipticity $[\theta]_\lambda$ (deg cm^2 dmol^{-1}): for 1.1 × 10^{-3} M (in CH_2Cl_2 at 25 °C) $[\theta]_{440}$ = −5280, $[\theta]_{386}$ = +14850, for 1.1 × 10^{-4}, $[\theta]_{341}$ = −1518, $[\theta]_{314}$ = +10890, $[\theta]_{270}$ = −82170.

Synthesis of 14. A solution of (R_C)-**4** (1.0 g) in 50 mL of dichloromethane was treated with 1,2-bis(diphenylphosphino)-ethane (0.6 g) and stirred for 4 h. Then, ethyl acetate was added to crystallize the diphosphine palladium complex.[8c,i] The resulting mixture was filtered through Celite into a three-neck round-bottom flask containing 0.4 g of $[(\eta^6\text{-}p\text{-cymene})RuCl_2]_2$, and the mixture was stirred for 3 h. To this solution was added 0.4 g of $AgCF_3SO_3$, and the mixture was stirred for 12 h. The resulting solution was filtered through Celite to remove AgCl. The red-orange filtrate was taken to dryness by rotary evaporation. The residue was dissolved in a minimum amount of dichloromethane and layered with ether to afford orange powders of a diastereomeric mixture of **14a** and **14b** in low yield (33%). These diastereomers could not be separated by fractional crystallization or column chromatography and were characterized only by $^{31}P\{^1H\}$ NMR spectroscopy in a ratio **14a**:**14b** = 20:3. $^{31}P\{^1H\}$ NMR (202.326 MHz, CD_2Cl_2, 25 °C): major (**14a**), δ 115.09 (s, 1P, P_7); minor (**14b**), δ 114.64 (s, 1P, P_2).

Typical Procedure for the Transfer Hydrogenation of Acetophenone. The catalyst precursors (0.05 mmol) and 2-propanol (40 mL) were added to a three-necked round-bottom flask and heated under reflux for 15 min. Then acetophenone (10 mmol) and KOH solution in 10 mL of 2-propanol (0.25 mmol) were introduced successively into the solution. The reaction mixture was stirred for half an hour. The solution was filtered through silica gel, and the solvent was subsequently removed by rotary evaporation. The resulting liquid was distilled under reduced pressure and analyzed by ^1H NMR spectroscopy. The enantiomeric excess was determined by ^1H NMR spectroscopy in $CDCl_3$ with the chiral shift reagent tris[3-(heptafluoropropylhydroxymethylene)-*d*-camphorato]-europium(III) (Eu(TFC)$_3$).

Acknowledgment. This research was supported by an award from the Research Corporation and by the donors of the Petroleum Research Fund Administered by the American Chemical Society. We are grateful for this support.

Supporting Information Available: Structural drawings of **6**, **7**, and **8a** and tables of crystal data and structural refinement, atomic coordinates, isotropic and anisotropic displacement parameters, bond lengths and bond angles, and hydrogen coordinates for **1**, **5b**, **6**, **7**, **8a**, **8b**, **10**, **12a**, and **12b**. This material is available free of charge at http://pubs.acs.org.

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