Asymmetric Hydrogenation Catalyzed by (*S,S*)-R-BisP*-Rh and (*R,R*)-R-MiniPHOS Complexes: Scope, Limitations, and Mechanism

Ilya D. Gridnev, Yoshinori Yamanoi, Natsuka Higashi, Hideyuki Tsuruta, Masaya Yasutake, Tsuneo Imamoto*

Department of Chemistry, Faculty of Science, Chiba University, Chiba 263-8522, Japan
Fax: +81-43-2 90-28 74; e-mail: imamoto@scichem.s.chiba-u.ac.jp

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Abstract: A new class of chiral C_2-symmetric bis-(trialkyl)phosphine ligands has been prepared and used in Rh(I)-catalyzed asymmetric hydrogenation reactions. The ligands, 1,2-bis(alkylmethylphosphino)ethanes **1 a–g** (abbreviated as BisP*, alkyl = *t*-butyl, 1-adamantyl, 1-methylcyclohexyl, 1,1-diethylpropyl, cyclopentyl, cyclohexyl, isopropyl) and 1,2-bis(alkylmethylphosphino)methanes **2 a–d** (abbreviated as MiniPHOS, alkyl = *t*-butyl, cyclohexyl, isopropyl, phenyl) are prepared by a simple synthetic approach based on the air-stable phosphine-boranes. These new ligands give the corresponding Rh(I) complexes, which are effective catalytic precursors for the asymmetric hydrogenation of a representative series of dehydroamino acids and itaconic acid derivatives. Enantioselectivities observed in these hydrogenations are universally high and in many cases exceed 99%. X-Ray characterization of four precatalysts, study of the pressure effects, deuteration experiments, and characterization of the wide series of intermediates in the catalytic cycle are used for the discussion of the possible correlation between the structure of the catalysts and the outcome of the catalytic asymmetric hydrogenation.

Keywords: asymmetric catalysis; amino acids; homogeneous catalysis; hydrogenations; P ligands; rhodium

Introduction

Catalytic asymmetric hydrogenation of dehydroamino acids and related compounds has recently been developed to a powerful method for producing a wide series of enantiomerically pure compounds.[1–4] Two stages of research in this area are clearly distinguishable. After the discovery of DIOP in 1972,[5] the following 20 years were marked by the development of new catalysts with chiral diphosphines bearing four aryl substituents on two phosphorus atoms. The elaboration of ligands such as DIPAMP,[6] CHIRAPHOS,[7] and BINAP[8] is one of the most important milestones in this research.

However, extensive studies of the hydrogenation reactions catalyzed by Rh(I) complexes with these ligands revealed also important limitations of their synthetic utility. For example, only low to moderate enantioselectivity could be obtained in the hydrogenations of *β*-branched dehydroamino acids. The extension of the scope of the catalytic asymmetric hydrogenation to substrates other than dehydroamino acids also proved to be very difficult.

This led to a search for new more effective diphosphine ligands for the Rh(I) catalyzed asymmetric hydrogenation. The most important advance was achieved with the introduction of the BPE and DuPHOS ligands.[9] The main distinctive feature of these diphosphines is the electron-rich character of the phosphorus atoms which is responsible for the high activity of corresponding Rh complexes, extending their applicability far beyond the hydrogenation of dehydroamino acids.[10–20] Another important structural feature of BPE and DuPHOS is the *pseudo*-chirality placed on phosphorus. This makes the enantioselection independent of the conformational properties of the chelate cycle that leads to high enantioselectivities.[9] However, comparatively modest results are observed for the BPE ligand relative to DuPHOS. This is stipulated for a greater conformational rigidity of the Rh chelate rings made by the latter ligand. Therefore, it was concluded[9] that the conformational rigidity of the chelate ring is another important factor for making a chiral diphosphine efficient as a ligand for the Rh(I) catalyzed asymmetric hydrogenation.

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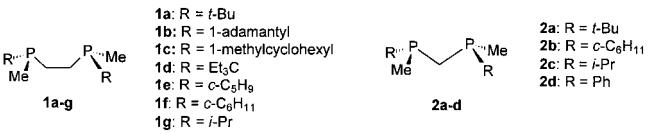
On the basis of these conclusions we have elaborated a new class of C_2-symmetric P-chirogenic phosphine ligands, the 1,2-bis(alkylmethylphosphino)-ethanes **1a-g** (alkyl = *t*-butyl, 1-adamantyl, 1-methylcyclohexyl, 1,1-diethylpropyl, cyclopentyl, cyclohexyl, isopropyl, abbreviated as BisP*) and the 1,2-bis(alkylmethylphosphino)methanes **2a–d** (alkyl = *t*-butyl, cyclohexyl, isopropyl, phenyl, abbreviated as MiniPHOS). Diphosphines **1a–g** contain a dimethylene chain similar to the BPE ligand. Nevertheless, they give conformationally more rigid Rh(I) complexes since the presence of the bulky alkyl groups stabilizes the conformation of the chelate ring in which these groups are *quasi*-equatorial.[21] The four-membered chelate ring in Rh(I) complexes of diphosphines **2a–d** is strictly conformationally rigid. On the other hand, the difference in size between the bulky and the smallest alkyl groups placed directly on the phosphorus atoms is an effective stereoregulating tool. Indeed, in preliminary communications we have shown a high efficiency of BisP*-Rh[22] and MiniPHOS-Rh[23] complexes for the hydrogenation of some α-(acylamino)acrylic derivatives including β-disubstituted ones.



Here we report the detailed investigations on the scope of the asymmetric hydrogenation of dehydroamino acids and itaconic acid derivatives catalyzed by the R-BisP*-Rh and R-MiniPHOS-Rh (R = Alkyl) catalysts. The work reported here addresses the following points which are relevant to the practical application of the new catalysts:

Preparation procedures for the chiral diphosphines, catalytic precursors, and active catalysts, the difficulties which may arise in these procedures and how they can be overcome.

Structural characterization of the catalytic precursors, correlation of the structural features elucidated from the X-ray data with the practical properties of the catalysts.

How the variation of the nature of the bulky groups may affect the enantioselectivities observed in the hydrogenation reactions.

Optimization of conditions for the highest effectivity of asymmetric hydrogenations; study of the pressure effects.

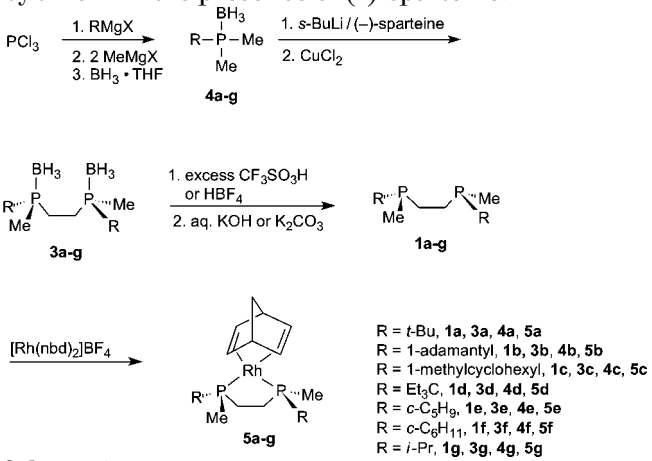
Characterization of intermediates in the catalytic cycle, correlation of the catalytic activities, and enantioselectivities obtained in asymmetric hydrogenations with the stability and structure of the observed intermediates.

Results and Discussion

Synthesis and Characterization of the Precatalysts

Synthesis of BisP* catalytic precursors 3 a–g

We have used the well-developed chemistry of phosphine–boranes[24–28] to prepare air-stable di(phosphine–boranes) **3a–g** by oxidative coupling of the corresponding alkyldimethylphosphine-boranes **4a–g** available via three-step one-pot synthesis starting from PCl_3 (Scheme 1). The chirality is introduced when phosphine–boranes **4** are deprotonated by *s*-BuLi in the presence of (–)-sparteine.[29]



Scheme 1

This reaction sequence was very effective for the preparation of tertiary di(phosphine–boranes) **3a–d**, which were obtained in 30–40% overall yield with >99% ee. The small admixtures of the corresponding *meso*-diastereomers were easily removed by recrystallization. The yields and enantiomeric purities of compounds **3e–g** were lower (20–30% yield, 70–80% ee). This is explained by the lower enantioselectivity of the deprotonation of the corresponding alkyl(dimethyl)phosphine–boranes. Enantiomerically pure phosphine–boranes **3e–g** were obtained by flash chromatography of the reaction mixture, removing the *meso*-diastereomers, followed by recrystallization. In the case of *i*-Pr substituted di(phosphine–borane) **3g**, a sample with only 80% ee was obtained after four recrystallizations, since the desired enantiomer is more soluble than the racemate.

Free phosphines **1a–g** were prepared from **3a–g** by deboronation with trifluoromethanesulfonic acid in toluene or with tetrafluoroboronic acid in dichloromethane, followed by treatment with aqueous KOH or K_2CO_3 (Scheme 1).[30], [31] The absolute configuration of the diphospine **1a** was determined by X-ray analysis of its TfOH salt **1a** · 2 TfOH. The absolute configuration of diphosphine **1f** was established by X-ray analysis of its Ru complex **1f** · $Ru(C_4H_7)_2$. The configurations of other three phosphines were assumed to be the same.

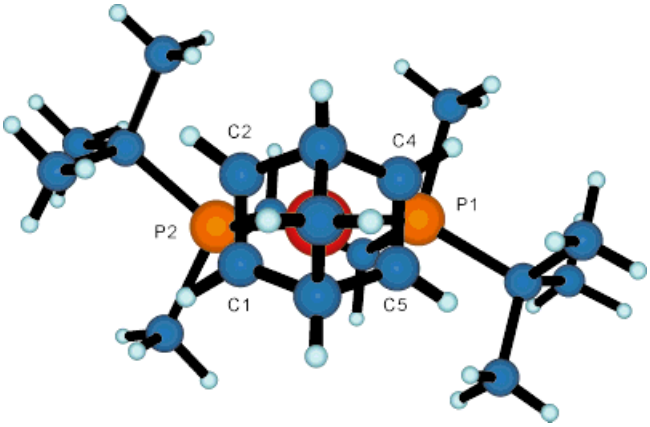


Figure 1. Crystal structure of **5 a.** The coordinated diene is only about 1° twisted clockwise

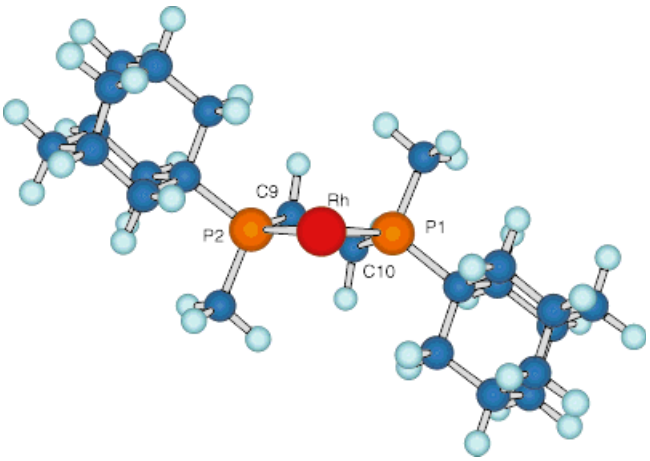


Figure 2. Crystal structure of **5 b** (norbornadiene omitted for clarity). λ-Conformation of the chelate cycle stabilized by *quasi*-equatorial orientations of bulky adamantyl substituents is clearly seen

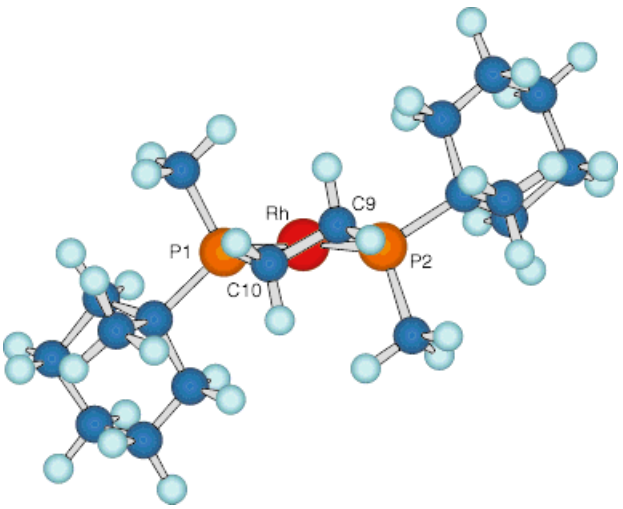


Figure 3. Crystal structure of **5 c** (norbornadiene omitted for clarity)

Table 1. Selected interatomic distances and intramolecular angles for [Rh((*R*,*R*)-**1 a**)(nbd)]BF_4,[a] [Rh(*R*,*R*)-**1 b**)(nbd)]BF_4,[b] and [Rh(*R*,*R*)-**1 b**) (nbd)]BF_4 (**5 c**)[c]

Compound	**5 a**	**5 b**	**5 c**
Interatomic distances (Å)			
Rh(1)–P(1)	2.314(1)	2.296(3)	2.305(2)
Rh(1)–P(2)	2.299(1)	2.302(3)	2.302(2)
Rh(1)–C(1)	2.200(4)	2.212(10)	2.225(7)
Rh(1)–C(2)	2.220(4)	2.22(1)	2.184(8)
Rh(1)–C(4)	2.216(4)	2.22(1)	2.214(8)
Rh(1)–C(5)	2.220(4)	2.19(1)	2.228(7)
C(1)–C(2)	1.370(6)	1.37(2)	1.37(1)
C(4)–C(5)	1.361(6)	1.36(2)	1.37(1)
Bond angles (deg)			
P(1)–Rh–P(2)	83.32(4)	83.8(1)	82.95(8)
C(1)–Rh–C(5)	65.8(2)	65.1(4)	66.3(3)
C(2)–Rh–C(5)	77.2(2)	76.3(4)	77.6(3)
C(1)–Rh–C(4)	76.8(2)	78.6(4)	77.9(3)
C(2)–Rh–C(4)	65.2(2)	66.1(4)	66.1(4)

[a] $C_{19}H_{36}P_2BF_4Rh$, FW = 516,15, orthorombic, $P2_12_12_1$, a = 20.500(8), b = 9.826(5), c = 11.517(3), V = 2319(1), Z = 4, D_{calc} = 1.48 g cm^{-3}, temperature of data collection –163 ± 1 °C.

[b] $C_{55}H_{56}P_2BF_4RhO$ (**5 b** + one THF molecule), FW = 744.48, orthorombic, $P2_12_12_1$, a = 11.773(3), b = 28.516(3), c = 30.190(9), V = 10135(4), Z = 12 (three molecules in asymmetric unit), D_{calc} = 1.46 g cm^{-3}, temperature of data collection –163 ± 1 °C.

[c] $C_{25}H_{44}P_2BF_4Rh$, FW = 596.28, orthorombic, $P2_12_12_1$, a = 9.825(2), b = 10.952(2), c = 24.068(5), V = 2589(1), Z = 4, D_{calc} = 1.53 g cm^{-3}, temperature of data collection –163 ± 1 °C.

Treatment of diphosphines **1 a–g** with $[Rh(nbd)_2]BF_4$ in THF gave precatalysts **5 a–g**. This reaction step was sometimes complicated by the simultaneous formation of corresponding $[Rh(BisP^*)_2]BF_4$ complexes, which became major products, if the corresponding cyclooctadienyl complexes were used. Recrystallization of **5 a–c** from appropriate solvent (see experimental section) allowed us to obtain analytically pure compounds **5 a–c**. In other cases the powders obtained by washing the crude product with hexane were characterized by NMR and used in the asymmetric hydrogenations. Since the complexes $[Rh(BisP^*)_2]BF_4$ contain the same chiral ligand, they cannot spoil the optical yields of asymmetric hydrogenation.

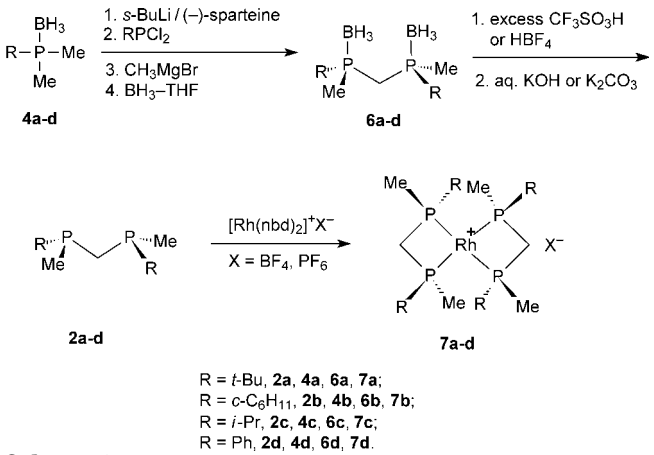
X-ray structure of the rhodium complexes 5 a–c

The structure of a catalyst precursor examined by X-ray crystallography helps to elucidate the important structural features of the newly designed catalyst. We have managed to obtain appropriate crystals for three BisP* catalytic precursors **5 a–c** (Figure 1–3). Selected interatomic bond distances and angles obtained from X-ray studies of the catalytic precursors **5 a–c** are given in Table 1. The structural features of **5 a–c** are essentially similar. Thus, all three X-ray

structures (Figure 1–3) show the C_2-symmetry and (*S*,*S*)-configuration of the coordinated diphosphines. The bulky alkyl groups occupy the *quasi*-equatorial positions thus effectively stabilizing the λ-conformation of the chelate cycles. The most folded area of the five-membered chelate cycle is carbon C9 as is clearly seen from the large torsion angles between both Rh–P bonds and the C9–C10 bond. The diene is almost symmetrically coordinated in either of **5 a–c**: the twist angles between the P–Rh–P plane and the plane defined by the NBD olefin midpoints do not exceed 3°. This observation is in contrast to the structures of other [(olefin)Rh(chiral diphosphine)]$^+X^-$ complexes, where considerable distortions from the square planar geometry are usually observed.[9,32–34] Moreover, the small deviations from the symmetric coordination of the diene correspond to the clockwise twist, which according to the empirical rule should lead to the production of *S*-amino acids in asymmetric hydrogenation. Since all three catalytic precursors give *R*-amino acids with very high ee's, we conclude that no correlation of the sign of the coordinated diene twist and enantioselectivity can be made in the case of BisP* catalysts.

Synthesis of catalytic precursors 7 a–d

Similar synthetic strategies based on the chemistry of air-stable phosphine–boranes have been used for the preparation of chiral diphosphines **7** (Scheme 2). Enantioselective deprotonation of dimethylalkylphosphine–boranes **4** followed by treatment of the resulting lithium salt with alkylphosphorus dichloride, methylmagnesium bromide, and borane–THF complex afforded optically active diphosphine–boranes **6** mixed with the corresponding *meso*-diastereomers. The pure diphosphine–boranes **6 a–d** were obtained in 13–28% overall yield by recrystallization from methanol or ethanol. The removal of the boranato groups with trifluoromethanesulfonic acid in toluene, followed by treatment with aqueous KOH provided the MiniPHOS **2 a–d** in almost quantitative yields.



Scheme 2.

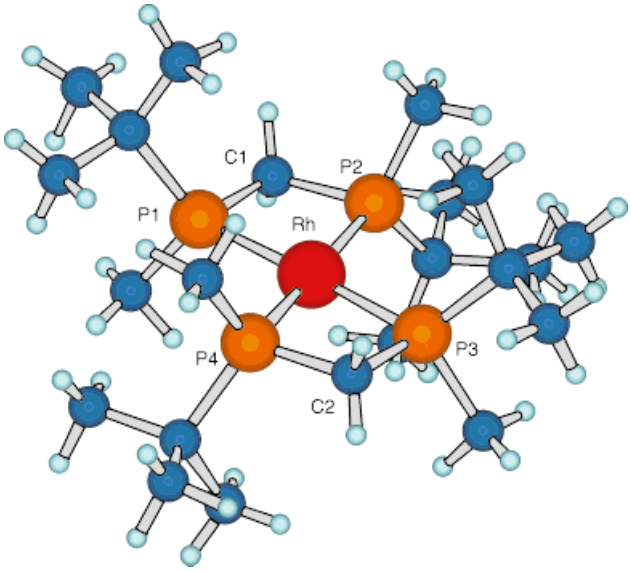


Figure 4. Crystal structure of **7 a**

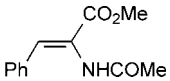
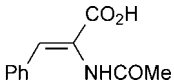
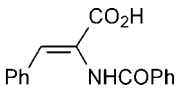
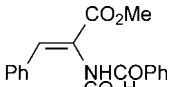
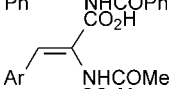
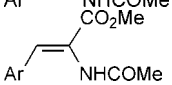
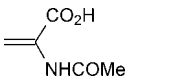
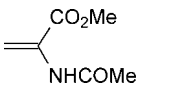
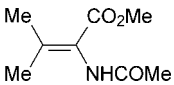
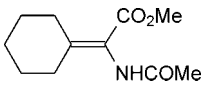
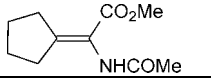
Table 2. Selected interatomic distances and intramolecular angles for [Rh{(*R*,*R*)-**7a**)}$_2$]PF_6[a]

Interatomic distances (Å)	
Rh–P(1)	2.309(4)
Rh–P(2)	2.307(4)
Rh–P(3)	2.352(4)
Rh–P(4)	2.323(4)
P(1)–C(1)	1.87(2)
P(2)–C(1)	1.91(1)
P(3)–C(2)	1.79(2)
P(4)–C(2)	1.81(2)
Bond angles (deg)	
P(1)–Rh–P(2)	72.8(1)
P(4)–Rh–P(3)	72.9(1)
Rh–P(1)–C(1)	97.7(5)
Rh–P(2)–C(1)	96.5(5)
Rh–P(3)–C(2)	92.7(5)
Rh–P(4)–C(2)	93.3(5)
P(1)–C(1)–P(2)	92.6(6)
P(3)–C(2)–P(4)	100.9(7)

[a] $C_{22}H_{52}P_5F_6Rh$, FW = 688.42, tetragonal, $P4_35$, a = 11.113(4), c = 27.301(5), V = 3371(1), Z = 4, D_{calc} = 1.36 g cm^{-3}, temperature of data collection 15 ± 1 °C.

The diphosphines **2** were reacted with [Rh(nbd)$_2$]$^+X^-$ (X = BF_4, PF_6). However, only bischelate complexes **7** could be obtained, even when excess of the rhodium complex was used in the reaction. Previously, James had reported use of [Rh(diop)$_2$]BF_4 in asymmetric hydrogenation.[35] He noted that the catalytic hydrogenation with bis(diop) species is much slower than the reaction with comparable mono(diop) systems, but can lead to higher optical yields.[35] Our preliminary results have shown a similar tendency for MiniPHOS-Rh complexes **7**.[23] We therefore studied further the asymmetric hy-

Table 3. Enantioselective hydrogenation of dehydroamino acids and their methyl esters catalyzed by alkyl-BisP*–Rh and alkyl-MiniPHOS–Rh

Entry	Substrate	Precatalyst	Solvent	H_2 (atm)	ee (%)[b]
1		**5a**	MeOH	2	**>99**
2		**5a**	*i*-PrOH	2	>99
3		**5b**	MeOH	2	**>99**
4		**5c**	MeOH	2	**>99**
5		**5d**	MeOH	2	95
6		**5d**	*i*-PrOH	2	95
7		**5e**	MeOH	2	43
8		**5e**	*i*-PrOH	2	40
9		**5f**	MeOH	2	47
10		**5f**	*i*-PrOH	2	30
11		**5g**	MeOH	2	17
12		**7a**	MeOH	1	**>99**
13		**7b**	MeOH	1	99
14		**5a**	MeOH	2	**98**
15		**5a**	EtOH	2	96
16		**5d**	EtOH	2	94
17		**7a**	MeOH	1	**98**
18		**5a**	MeOH	2	**96**
19		**5a**	EtOH	13	88
20		**5d**	EtOH	2	53
21		**7a**	MeOH	1	**97**
22		**5a**	MeOH	2	98
23		**5d**	*i*-PrOH	2	90
24		**5a**	MeOH	2	97
25		**5a**	EtOH	4	**98**
26		**5d**	MeOH	2	95
27		**5a**	MeOH	2	**>99**
28		**5a**	*i*-PrOH	4	98
29		**5d**	*i*-PrOH	2	85
30		**5e**	*i*-PrOH	2	22
31		**7a**	MeOH	2	95
32		**5d**	EtOH	2	42
33		**5e**	EtOH	2	33
34		**7a**	MeOH	1	**>99**
35		**7b**	MeOH	1	99
36		**7c**	MeOH	1	98
37		**7d**	MeOH	1	26
38		**5a**	MeOH	2	98
39		**5b**	MeOH	2	**>99**
40		**5e**	EtOH	2	80
41		**7a**	MeOH	1	**>99**
42		**7b**	MeOH	1	99
43		**7c**	MeOH	1	98
44		**5a**	MeOH	4	36
45		**5a**	C_6H_6	4	55
46		**5c**	MeOH	2	25
47		**5e**	MeOH	2	**91**
48		**5f**	MeOH	4	47
49		**5g**	MeOH	6	39
50		**7a**	MeOH	6	87
51		**7b**	MeOH	6	85
52		**5a**	MeOH	4	84
53		**5a**	C_6H_6	4	84
54		**5b**	MeOH	4	82
55		**5d**	MeOH	5	20
56		**5e**	MeOH	6	**93**
57		**5f**	MeOH	6	89
58		**7a**	MeOH	6	**97**
59		**7b**	MeOH	6	94
60		**7c**	MeOH	6	83
61		**7a**	MeOH	6	**94**
62		**7b**	MeOH	6	90
63		**7c**	MeOH	6	88

[a] Reactions were carried out at room temperature using 0.2 mol % of catalytic precursors. Conversion was 100%. The reaction time was 1 h in the case of catalytic precursors 5 and 24 h in the case of **7**. The ee (%) values were determined either by HPLC using Daicel Chiral OJ or OD-H columns, or by chiral capillary GC using a Chrompack Chiral-L-Val column.

[b] In all cases *R*-isomers were obtained; the absolute configurations were confirmed by comparison of sign of optical rotation and chiral HPLC or GC elution order with those of configurationally defined samples.

drogenation with Rh(I) complexes **7** as catalytic precursors.

X-ray structure of the rhodium complex 7 a

The X-ray structure of the [Rh((*R,R*)-*t*-Bu-MiniPHOS)$_2$]$^+$PF$_6^-$ **7 a** is shown in Figure 4. The overall C_2-symmetry of the complex and the *R,R*-configuration of the diphosphine directly follow from Figure 4. Two chelate cycles have notably different geometries (compare the corresponding bond lengths and bond angles in Table 2).

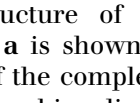
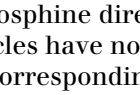
Asymmetric hydrogenation of dehydroamino acids, itaconic acid, and its methyl ester

The possibility to produce enantiomerically pure amino acids, including unnatural compounds, was the most impressive achievement of the catalytic asymmetric hydrogenation sustaining the continuing interest to this field. It has become a tradition to compare various catalysts by their effectivity in the reduction of (*Z*)-α-(acylamino)acrylates. On the other hand, one of the important features of the newly designed catalysts, BisP* and MiniPHOS, is their tunability, i. e., the possibility to regulate the exact manner of enantioselectivity by changing the alkyl groups on the phosphorus atoms. We therefore carried out an extensive series of hydrogenations in order to evaluate the effectivity of the new catalysts, estimate the scope of their applicability, find out the optimal conditions, and tune the enantioselectivity by appropriate choice of the alkyl substituents on the phosphorus atoms.

The results of this study are summarized in Table 3. The main conclusion, which can be drawn from the Table, is the high effectivity of the BisP*–Rh and MiniPHOS–Rh catalysts: for a wide series of dehydroamino acids enantioselectivities of over 97% were achieved for β-unsubstituted substrates, (entries 1–43), and of over 90% for β-branched dehydroamino acids (entries 44–63). Another important conclusion is the high catalytic activity of the BisP*–Rh catalysts: all hydrogenations were complete within 1 hour at room temperature and a starting pressure of H_2 of 2 atm. However, higher H_2 pressure (4 atm) is required to reduce β-branched dehydroamino acids. A activity of the MiniPHOS-Rh catalysts is lower, and approximately 1 day at room temperature is required to achieve 100% conversion at the starting pressure of H_2 of 1 atm (6 atm in the case of β-branched substrates). Similar conversion times are characteristic to CHIRAPHOS-Rh catalysts,[36,37] but the enantioselection in the case of **7a** is much higher.

The optimal solvent for the hydrogenation is methanol; changing it to isopropanol (entries 2, 6, 8, 10, 23, 28–30) or to ethanol (entries 15, 16, 19, 20, 25, 32, 33, 40) has never resulted in an improvement of the enantiomeric excess, but required sometimes harsher conditions for completeness of the reaction.

Table 4. Enantioselective hydrogenation of itaconic acid and its methyl ester catalyzed by alkyl-BisP*–Rh and alkyl-MiniPHOS–Rh

Entry	Substrate	Catalyst	ee (%)
1		5 a	98.6
2		5 c	99.6
3		7 a	99.9
4		7 a	99.9
5		7 a	98.0

[a] The hydrogenations were carried out under the same conditions as specified in Table 3.

The use of benzene allowed us to increase ee's in two cases (entries 45 and 53), however the reduction was incomplete due to the high complexing ability of benzene.

Variation of the alkyl substituents on the phosphorus atoms (Table 3) showed that *t*-Bu–BisP*–Rh (**5 a**) and *t*-Bu–MiniPHOS–Rh (**7 a**) catalysts are optimal for the hydrogenation of the β-unsubstituted and β-monosubstituted dehydroamino acids. Comparable results are obtained for Ad–BisP*–Rh (**5 b**, entries 3 and 39) and for 1-methylcyclohexyl–BisP*–Rh (entry 4). However, the Et$_3$C–BisP*–Rh precatalyst **5 d** containing an even bulkier group than *t*-Bu gives lower enantioselectivities than **5 a–c** (entries 5, 6, 16, 20, 23, 29, 32, 55).

Although BisP*–Rh catalysts with cyclopentyl (**5 e**) and cyclohexyl (**5 f**) substituents gave rather inferior results in the hydrogenation of β-unsubstituted substrates (entries 7–10, 16, 20, 23, 29, 32), they proved to be the most effective BisP* catalysts for the reduction of β-branched dehydroamino acids (entries 47 and 56). This finding demonstrates the effectivity of the ligand tuning, which is based on the most close matching of the structures of the catalyst and the substrate. Nevertheless, among the studied MiniPHOS catalysts, the *t*-Bu MiniPHOS (**7 a**) proved to be the most effective one for the hydrogenation of β-branched substrates either (entries 58 and 61).

Thus, the asymmetric hydrogenation catalyzed by BisP*–Rh and MiniPHOS–Rh catalysts gives high enantioselectivities for a wide range of dehydroamino acids. The reaction conditions are mild, and the structure of the catalyst can be tuned to match optimally the exact structure of the substrate.

The asymmetric hydrogenation of itaconic acid derivatives is a potential synthetic approach to many useful products.[17] However, the enantioselectivities in such reactions are often notably lower when compared to those in the reduction of dehydroamino acids. We have found that *t*-Bu–BisP* **5 a**, Ad–BisP* **5 b**, and *t*-Bu–MiniPHOS **7 a** give excellent results in the hydrogenation of itaconic acid and its methyl ester (Table 4).

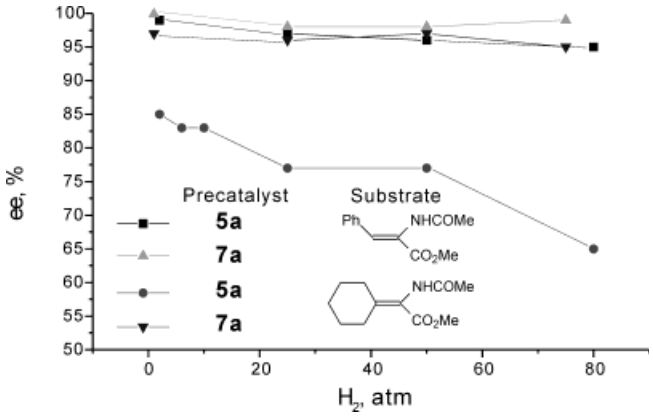


Figure 5. Pressure dependence of the optical yields in the asymmetric hydrogenations catalyzed by **5 a** and **7 a**

Summarizing the studies of the asymmetric hydrogenations catalyzed by BisP* and MiniPHOS catalysts, one can see that these catalytic systems are applicable to a wide range of prochiral dehydroamino acids providing high to excellent enantioselectivity in the majority of cases. The catalytic activity of the BisP*–Rh complexes is comparable to that of the best known DuPHOS–Rh catalysts.

Hydrogenations at High Pressure

Lower catalytic activities of the MiniPHOS based Rh(I) catalysts induced us to probe the high-pressure hydrogenation of dehydroamino acids. Figure 5 shows the dependence of the optical yields of the asymmetric hydrogenations using **5 a** and **7 a** as precatalysts on the pressure of H_2. The results obtained for the BisP* catalyst **5 a** are diverse depending on the substrate used. Thus, the ee of (*R*)-phenylalanine is only slightly reduced from >99% at 2 atm of H_2 to 97% at 75 atm. On the other hand, the relatively low ee obtained for *β*,*β*-disubstituted substrate at 2 atm of H_2 becomes notably lower at 75 atm.

Interestingly, this effect is apparently absent for the MiniPHOS precatalyst **7 a**: both substrates give very high ee's which almost do not change with the increasing pressure. In practice, this means that the high pressure of hydrogen can be applied in asymmetric hydrogenations catalyzed by MiniPHOS catalysts in order to compensate for their relatively low catalytic activity.

Mechanistic Studies

In spite of the extensive studies carried out over the last three decades, a complete understanding of the mechanism of enantioselection in asymmetric hydrogenation has not yet been achieved.[1] From the practical point of view, it would be highly desirable if the mechanistic studies would be able to give some useful hints about the design of the catalysts and optimization of the reaction conditions. However, on analyzing the present state of research one must admit that any existing practical recommendations (e. g., the conformational rigidity of the chelate cycle, etc.) arise rather from the accumulated experimental facts than follow from the mechanistic studies. In this work we attempted to search for a correlation between the observed optical yields and the properties of characterizable intermediates, using extensive hydrogenation data and analyzing a wide series of intermediates.

We have shown recently that the mechanistic features of the asymmetric hydrogenation catalyzed by **5 a** may differ notably from all previously reported cases.[38] Thus, a solvate dihydride **9a** has been characterized for the first time (Scheme 3). The dihydride **9 a** at –100 °C undergoes fast reaction with methyl (*Z*)-*α*-acetamidocinnamate producing the monohydride intermediate **11 a**. The latter intermediate undergoes reductive elimination at temperatures above –50 °C producing a catalyst-product complex **12 a,** which dissociates reversibly yielding the hydrogenation product and regenerating the solvate complex **8 a** (Scheme 3).

These findings testify that the dihydride mechanism, in which the hydrogenation of the catalyst occurs first, is feasible for this reaction.[38] Here we examine the scope of the above observations, and examine their probable correlation with the results of asymmetric hydrogenation.

Table 5. NMR and thermodynamic parameters for characterized solvate complexes **8** and dihydrides **9**

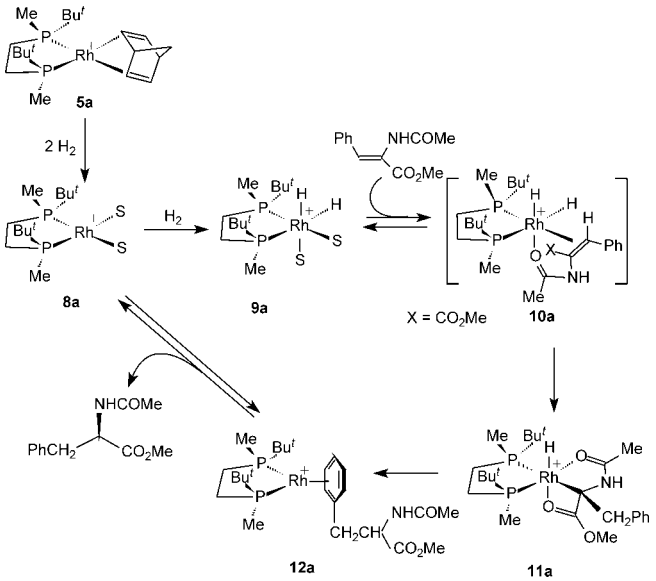
	8	**9**				Equilibrium between **8**, **9**, and H_2		
	$\delta^{31}P$ ($^1J_{Rh,P}$)	δ^1H_{trans} ($^1J_{Rh,H}$, $^2J_{P,H}$)	δ^1H_{cis} ($^1J_{Rh,H}$, $^2J_{P,H}$)	$\delta^{31}P_{trans}$ ($^1J_{Rh,P}$)	$\delta^{31}P_{cis}$ ($^1J_{Rh,P}$)	Ratio **9** : **9′**	*ΔH*	*ΔS*
8 a, **9 a**	89.8 (204)	–7.7 (19, 186, 19)	–22.9 (29, 14, 29)	43.8 (86)	95.0 (145)	10 : 1	–6.3	–23.7
8 b, **9 b**	87.7 (202)	–7.7 (18, 184, 18)	–23.1 (28, 13, 28)	37.7 (86)	93.7 (147)	>20 : 1	–6.6	–25.7
8 c, **9 c**	93.1 (204)	–7.9 (18, 188, 18)	–23.2 (28, 15, 28)	44.1 (82)	98.8 (146)	12 : 1	–7.4	–28.5
8 e, **9 e**	78.7 (202)	–7.6 (18, 188, 18)	–22.6 (29, 13, 29)	32.4 (89)	87.4 (146)	[a]	[a]	[a]

[a] Not determined due to the presence of impurities.

Table 6. Chemical shifts and coupling constants (Hz) in the ^{1}H NMR spectra (500 MHz, CD_3OD, 253 K) of the catalyst-substrate complexes **13a–c**, and **14–16**

Compound	**13a**	**13b**	**13c**	**14**	**15**	**16**
δ_R[a] ($^2J_{H,P}$)	0.70 (15)	1.47 (br.s) 1.72 (br.s)[c]	0.72 (18)[c]	0.74 (15)	1.20 (14)	1.12 (14)
δ_R[b] ($^2J_{HP}$)	1.18 (14)	1.85 (br.s) 2.01 (br.s)[c]	1.22 (15)[c]	1.20 (14)	1.12 (15)	1.13 (15)
$\Delta\delta_R$	0.48	0.38	0.50	0.46	–0.08	–0.08
δ_{Me}[a] ($^2J_{H,P}$)	1.42 (9)	1.38 (9)	1.38 (8)	1.42 (9)	1.51 (10)	1.59 (9)
δ_{Me}[b] ($^2J_{H,P}$)	1.59 (10)	1.53 (10)	1.53 (10)	1.58 (10)	1.42 (9)	1.48 (11)
$\delta(CH_2)$[a]	2.55	2.55	2.50	2.48	2.23	2.35
$\delta(CH_2)$[b]	2.19	2.30	2.20	2.18	2.13	2.20
δ_{CH} = ($^3J_{H,P}$, $^2J_{H,Rh}$)	6.08 (5, 3)	6.04 (5, 3)	5.93 (5, 3)	6.12 (4, 3)	2.62, 3.59	3.06, 4.18
δ_{MeCO}	2.33	2.33	2.30	2.20	2.11	–[d]
δ_{OMe}	3.79	3.80	3.75	–	–	3.64, 3.89
δ_{Ph}	7.35–7.45	7.35–7.50	7.3–7.40	7.35–7.45	–	–

[a] Alkyl group attached to the high-field phosphorus.
[b] Alkyl group attached to the low-field phosphorus.
[c] Other signals give unresolved multiplets between 1.0 and 2.0 ppm.
[d] $\delta(CH_2)$ = 3.11 ($^2J_{H,H}$ = 20.5 Hz, $^4J_{H,P}$ = 9.5 Hz); 4.02 ($^2J_{H,H}$ = 20.5 Hz).

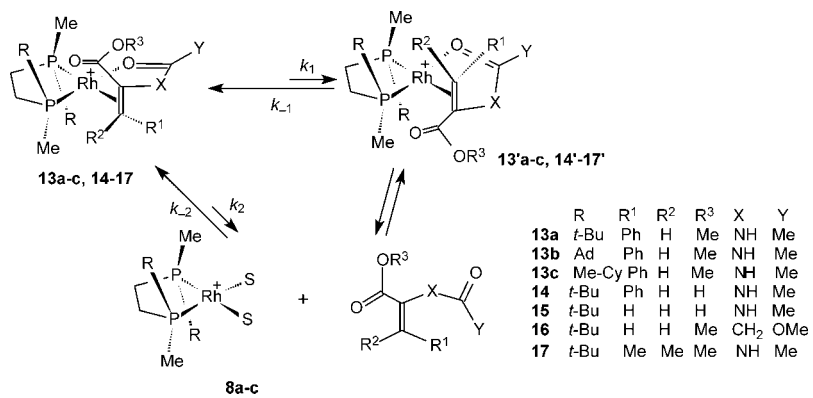


Scheme 3.

Formation of Solvate Dihydrides

Similar to **5a**, **the** catalytic precursors **5b, c** cleanly gave the corresponding solvate complexes **8b, c** upon hydrogenation in deuteromethanol at –20 °C. Further hydrogenation at –100 °C yielded equilibrium concentrations of dihydrides **9b,c** which were characterized by their ^{1}H NMR and ^{31}P NMR spectra, including 2D ^{1}H, ^{31}P correlations and heteronuclear selective decoupling experiments (Table 5). The equilibria between the solvate complexes **8b,c**, dihydrides **9b,c**, and dihydrogen in deuteriomethanol were studied in the temperature interval from –90 to –60 °C using the integrated intensities of the corresponding signals in the ^{1}H and ^{31}P NMR spectra, as described previously.[38]

Dihydrides **9e, f** were also generated from the catalytic precursors **5e, f**, but in these cases the admixtures of the corresponding $[Rh(BisP^*)_2]BF_4$ complexes made impossible the complete characterization of the



	R	R^1	R^2	R^3	X	Y
13a	*t*-Bu	Ph	H	Me	NH	Me
13b	Ad	Ph	H	Me	NH	Me
13c	Me-Cy	Ph	H	Me	NH	Me
14	*t*-Bu	Ph	H	H	NH	Me
15	*t*-Bu	H	H	H	NH	Me
16	*t*-Bu	H	H	Me	CH_2	OMe
17	*t*-Bu	Me	Me	Me	NH	Me

Scheme 4.

Table 7. Chemical shifts and coupling constants (Hz) in the ^{31}P NMR spectra (202 MHz, CD_3OD) of the catalyst-substrate complexes **13a–c**, and **14–16**[a]

Compound	**13a**[b]	**13b**	**13c**	**14**[b]	**15**[c]	**16**[c]
$\delta_{P\text{-}1}$ ($^1J_{Rh,P}$)	76.34 (158)	70.13 (157)	76.58 (157)	75.58 (160)	74.08 (151)	74.37 (156)
$\delta_{P\text{-}2}$ ($^1J_{Rh,P}$)	79.65 (157)	75.10 (155)	82.20 (157)	78.9 (159)	76.48 (148)	80.91 (160)
$^2J_{P,P}$	31	31	29	31	30	30

[a] Averaged spectra.
[b] At 298 K.
[c] At 253 K.

equilibria. The NMR data for solvate complexes **8a–c, e** and dihydrides **9a–c, e**, as well as the thermodynamic parameters of the equilibria are listed in Table 5.

It should be noted that the oxidative addition of dihydrogen to solvate complexes **8a–c** is highly stereoselective: the diastereomeric ratio of dihydrides **9** and **9′** varies from 10:1 to 20:1. The observed ratios did not change when the temperature was varied within the interval from –100 to –50 °C. We conclude therefore that the observed selectivity of H_2 oxidative addition is under thermodynamic control, and reflects the relative stability of the diastereomers **9** and **9′**.

Recently, Landis et al. reported the high kinetic selectivity in the H_2 addition to Ir complexes of some chiral diphosphines.[39] The equilibrium concentrations of certain dihydrides (NORPHOS, CHIRAPHOS) were found to differ notably from the kinetic ratios. On the other hand, DIOP and BINAP Ir complexes demonstrated selectivities remaining virtually unchanged with temperature, which resembles the behavior of the dihydrides **9a–c**. Since both BINAP and BisP* catalysts exhibit extremely high enantioselectivities in the Rh-catalyzed asymmetric hydrogenations, we conclude that the high equilibrium stereoselectivity of the oxidative addition of dihydrogen to the corresponding complexes may be of some importance for the most successful asymmetric hydrogenations. The formation of dihydrides **10a–c** is an equilibrium stage, and it cannot therefore be a main stereoregulating factor. Nevertheless, the "correct" equilibrium stereoselectivity of dihydrogen oxidative addition might facilitate the further stereoselection, so improving the overall optical yields.

Catalyst-Substrate Complexes

For many years the catalyst-substrate complexes were the most frequently characterized intermediates in the asymmetric hydrogenation of dehydroamino acids. Extensive data have been acquired, which display a considerable diversity in the solution properties of these species.[40–58] Here we report the study of the structure and dynamic behavior in deuteriomethanol solutions of the catalyst-substrate complexes **13a–c** generated by the reactions of methyl (*Z*)-α-acetamidocinnamate with **5a**, **5b**, and **5c**, as well as complexes **14–17** of **5a** with (*Z*)-α-acetamidocinnamic acid, (*Z*)-α-acetamidoacrylic acid, dimethyl itaconate, and methyl β,β-dimethyl-(*Z*)-α-acetamidocinnamate.

The solution behavior of all studied catalyst-substrate complexes is generalized in Scheme 4. In all studies cases one diastereomer of a catalyst-substrate complex predominates in solution. The complete NMR data for the major diastereomers of the catalyst-substrate complexes are given in Table 6–8. Two

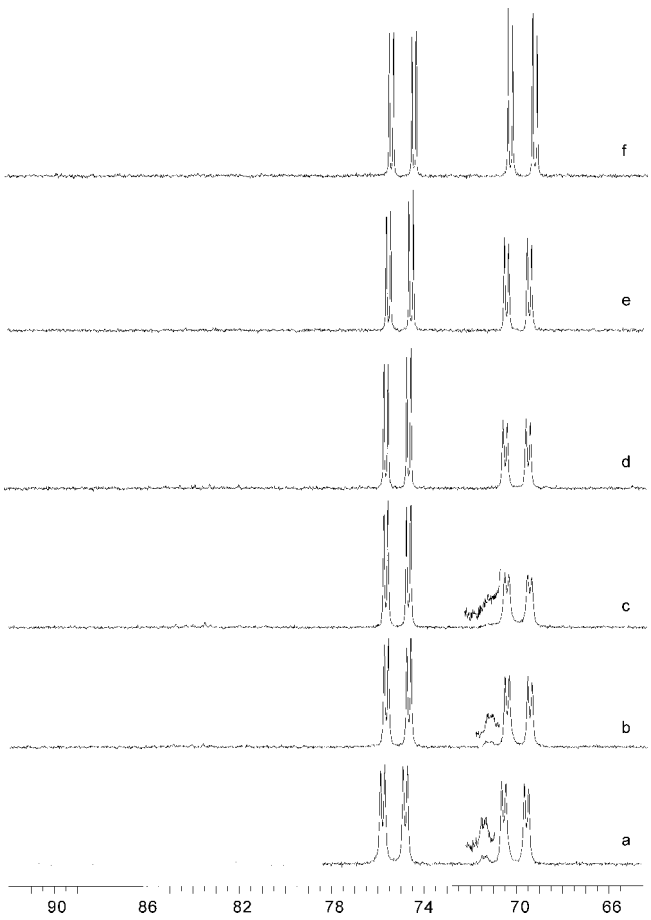


Figure 6. Dependence of the line shape in the ^{31}P NMR spectrum (162 MHz, CD_3OD) of **13b** on the temperature: a) at –90 °C; b) at –80 °C, c) at –70 °C; d) at –40 °C, e) at –20 °C; f) at 30 °C

Table 8. Chemical shifts and coupling constants (Hz) in the ^{13}C NMR spectra (125 MHz, CD_3OD, 253 K) of the catalyst-substrate complexes **13a–c**, and **14–16**[a]

Compound	**13a**	**13b**	**13c**	**14**	**15**	**16**
δ_R[b] ($J_{C,P}$)	25.80 (5) 34.52 (32)	29.22 (CH_2, 9) 37.14 (CH_2) 37.39 (CH) 38.66 (C_{tert}, 31)	17.80 (Me, 7) 21.51 (CH_2, 10) 26.83 (CH_2) 31.72 (CH) 38.64 (C_{tert}, 33)	25.85 (4) 34.85 (32)	26.28 33.84 (28)	26.83 (3.5) 33.80 (30)
δ_R[d] ($J_{C,P}$)	28.86 (4) 32.38 (29)	29.95 (CH_2, 9) 37.55 (CH_2) 41.02 (CH) 35.76 (C_{tert}, 26)	19.67 (Me) 22.17 (CH_2, m) 26.37 (CH_2) 32.09 (CH) 35.86 (C_{tert}, 29)	26.71 34.07 (30)	27.18 33.61 (27)	26.93 (3) 33.58 (30)
δ_{Me}[b] ($^1J_{C,P}$)	7.96 (20)	6.15 (20)	6.86 (20)	7.98 (20)	6.83 (27)	8.67 (25)
δ_{Me}[c] ($^1J_{C,P}$)	7.13 (27)	5.87 (28)	6.16 (27)	7.27 (29)	7.85 (32)	8.69(19)
$\delta(CH_2)$[b] ($^1J_{C,P}$, $^2J_{C,P}$, $^2J_{C,Rh}$)	21.14 (35, 8, 3)	19.74 (29, 8, 4)	20.74 (28, 7, 3)	25.29[d]	26.56[d]	23.40 (28)[d]
$\delta(CH_2)$[c] ($^1J_{C,P}$, $^2J_{C,P}$, $^2J_{C,Rh}$)	32.56 (33, 19, 4)	31.65 (34, 19, 4)	32.18 (33, 21, 4)	33.62 (37, 11, 5)	33.80 (28, 16)[d]	29.22[e] (37, 21)[d]
δ_{CH} = ($^2J_{C,P}$)	79.33 (14)	78.86 (14)	78.21 (14)	80.33 (13)	62.48 (15)	51.15 (14)
δ_C = ($^2J_{C,P}$, $^1J_{C,Rh}$)	80.92 (23, 6)	81.08 (24, 8)	80.29 (23, 8)	80.06 (34)[d]	[f]	53.52 (29)[d]
$\delta_{O=C=O}$ ($^2J_{C,Rh}$)	169.86 (5)	170.02 (5)	170.06 (4)	168.72	166.83	–
$\delta_{N=C=O}$ ($^2J_{C,Rh}$)	186.10 (8)	186.12 (7)	186.02 (6)	173.43	182.05	175.45 (5), 190.47 (5)
δ_{MeCO}	20.12	20.12 (2)	20.27	22.61[g]	22.8[g]	–
δ_{OMe}	53.18	53.10	53.17	–	–	52.06, 55.78
δ_{ipso} ($^3J_{C,P}$)	139.74 (2)	140.42 (2)	140.04 (2)	139.71	–	–
$\delta_{o,m,p}$	129.47, 130.75, 131.13	129.08, 131.78, 131.19	129.60, 130.89, 131.13	129.73, 130.80, 130.90	–	–

[a] Averaged spectra.
[b] Alkyl group attached to the high-field phosphorus.
[c] Alkyl group attached to the low-field phosphorus
[d] Some couplings were not measured due to small values or overlapping with other signals.
[e] $\delta(CH_2$ from *itac*) = 38.45, $^3J_{C,P}$ = 4.1 Hz).
[f] Signal was not found.
[g] $^4J_{CP}$ = 4.1 Hz.

diastereomers can interconvert in each case both intramolecularly and intermolecularly via complete dissociation to solvate complex **8** and corresponding substrate. In all studied cases ($k_1 + k_{-1}$) was much greater than ($k_2 + k_{-2}$).

The structures of the major isomers **13a–c** and **14** were elucidated on the basis of the chemical shifts and NOE data, in the same fashion as we have already reported for **13a**.[38] Thus, on analyzing the relative positions of two different *t*-Bu groups in the ^1H NMR spectrum of each catalyst-substrate complex (Table 6), one can see that in all cases when the phenyl group is present in *β*-position a considerable high-field shift of one of the *t*-Bu groups is observed. The same is valid for the methyl group from one of the methylcyclohexyl substituents in **13c** and for the one set of three CH_2 groups in **13b**. This effect is completely absent in the catalyst-substrate complexes that do not contain a phenyl substituent. Therefore, one of the *t*-Bu groups resonates at a higher field due to the shielding of the adjacent phenyl ring. Furthermore, the NOE's between the olefinic proton and one of the methyl groups found in the phase-sensitive NOESY spectra of **13a–c** and **14** give enough reasons to assign their structures. The enamides are *re*-coordinated in all these complexes, but catalytic hydrogenation affords *R*-amino acids with high enantioselectivity.

The catalyst-substrate complexes **13a–c** and **15** exhibit very similar dynamic behavior in solution (e. g., Figure 6). At –90 °C two species are observed in a ratio of approximately 10 : 1 (**13a–c**) or almost 1 : 1 (**15**), which are in a fast exchange and their signals collapse at the temperatures –72 °C (**13a**), –60 °C (**13b–c**), and –80 °C (**15**). The binding of the substrates is strong in these complexes: no detectable amount of corresponding solvate complexes **8a–c** was found in their NMR spectra in the studied temperature interval from –95 to +50 °C. Nevertheless, small undetectable equilibrium amounts of **8a–c** are present, since the EXSY data testify for the intermolecular exchange occurring at ambient temperature.[38]

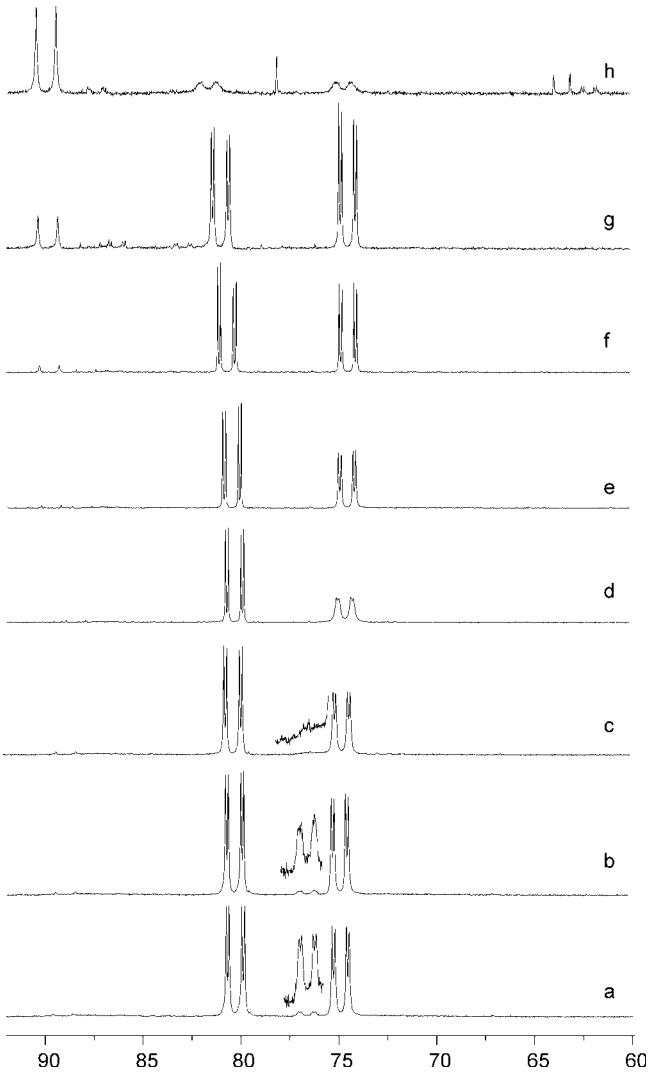


Figure 7. Dependence of the line shape in the ^{31}P NMR spectrum (202 MHz, CD_3OD) of **16** on the temperature: a) at –95 °C; b) at –90 °C; c) at –80 °C, d) at –60 °C (T_c); e) at –40 °C, f) at –20 °C; g) at 0 °C; h) at 25 °C

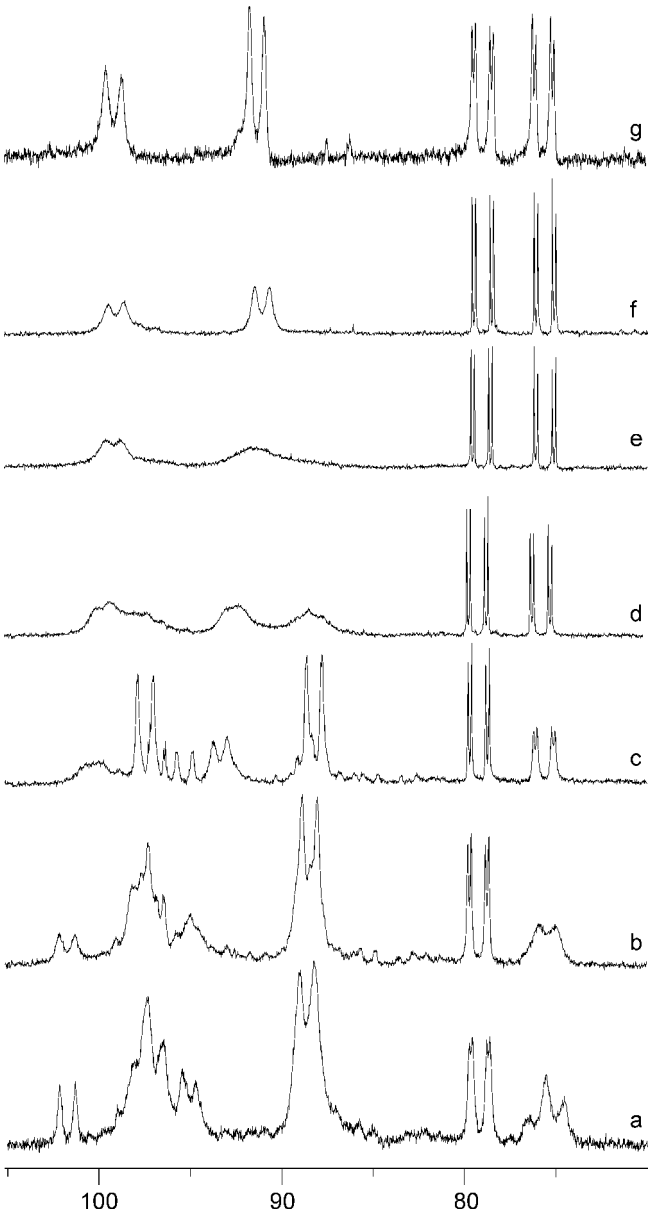


Figure 8. Dependence of the line shape in the ^{31}P NMR spectrum (162 MHz, CD_3OD) of **14** on the temperature: a) at –97 °C; b) at –90 °C; c) at –70 °C, d) at –40 °C; e) at –20 °C; f) at 20 °C; g) at 60 °C

In the case of the catalyst-substrate complex **16** of **8 a** with dimethyl itaconate, the binding of the substrate is weaker, and considerable equilibrium concentrations of free **8 a** are seen in the NMR spectra taken above –50 °C (Figure 7). Nevertheless, the low-temperature ^{31}P NMR spectra are very similar to those of **13 a–c** and **15**: two species present in a ratio 12:1 are in a fast equilibrium. The intramolecular exchange of **16** and **8 a** is relatively fast, and manifests itself by way of line broadening in the ^{31}P NMR spectra at –20 °C (Figure 7). A very similar temperature dependence of a catalyst-substrate complex with dimethyl itaconate was recently reported.[55]

The catalyst-substrate complex **14** of **8 a** with (*Z*)-α-acetamidocinnamic acid exhibits a more complex dynamic behavior in solution. Figure 8 illustrates the temperature dependence of the ^{31}P NMR spectrum obtained by addition of two equivalents of (*Z*)-α-acetamidocinnamic acid to the solution of solvate **8 a** in deuteromethanol. Two sharp multiplets in the spectrum at 293 K correspond to the nonequivalent phosphorus atoms of the catalyst-substrate complex **14**. Besides, two broad signals at 91.2 and 99.0 ppm are observed, which sharpen reversibly when temperature is raised to 60 °C (Figure 7). Decreasing the temperature leads to reversible changes of all signals in the spectrum. The signals of **14** demonstrate a very similar temperature dependence to that of **13 a–c**: the high-field multiplet broadens considerably at –90 °C, whereas the low-field multiplet remains relatively sharp. Two broad doublets become still broader when

Table 9. Parameters of the ^{1}H and ^{31}P NMR spectra of the monohydride intermediates **18 a–c**

Compound	δH ($^{1}J_{Rh,H}$, $^{2}J_{P,H}$)	δ^{31}P1 ($^{1}J_{R,hP}$)	δ^{31}P2 ($^{1}J_{R,hP}$)	$^{2}J_{P,P}$
18 a	–23.0 (28, 16, 28)	60.0 (136)	70.2 (93)	15
18 b	–23.4 (30, 18, 30)	51.5 (163)	[a]	[a]
18 c	–23.6 (27, 16, 27)	60.8 (133)	71.1 (100)	18

[a] Not determined due to the low stability of **18 b**.

the temperature is decreased, and at –70 °C each produces three doublets, which also broaden on further lowering of the temperature.

The structure of the species producing numerous exchanging resonances with the ^{31}P chemical shifts in the range 90–110 ppm is obscure. Relatively small values of the Rh–P coupling constants for these signals (125–135 Hz) suggest that they may belong to terdentate Rh complexes in which the metal is coordinated by the double bond, as well as the carboxylic, and the acetamido groups.[44] However, the broad signals in the ^{1}H and ^{13}C NMR spectra hinder further structure elucidations. The content of **14** in the equilibrium changes from 25% at –95 °C to 50% at 60 °C.

Similar effects in the considerably more complex NMR spectra of catalyst-substrate complexes derived from dehydroamino acids have been reported previously.[48,56] Note, however, that the equilibrium concentration of a similar by-product of the catalyst-substrate complex with acrylic acid is very low.

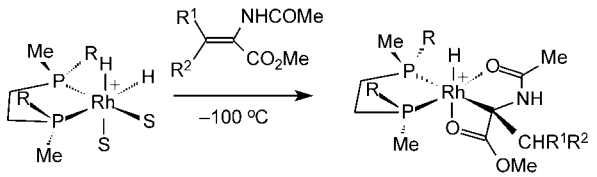
The solution behaviors of the BisP*-substrate complexes **13 a–c** and **14–16** differ in many points. Thus, the ratio of the diastereomers at low temperature varies from 10 : 1 in **13 a–c** and 12 : 1 in **16** to 3 : 1 in **14**, and approximately 1 : 1 in **15**. No detectable concentrations of other compounds in the equilibrium were found in the NMR spectra of **13 a–c** and very small amounts were seen in the spectra of **15**. But **16** equilibrates with a considerable amount of **8 a**, whereas the equilibrium mixture contains only 25% of **14** at –95 °C.

However, all four substrates: methyl (*Z*)-α-acetamidocinnamate, (*Z*)-α-acetamidocinnamic acid, α-acetamidoacrylic acid, and dimethyl itaconate give enantioselectivities of over 98% in the hydrogenations catalyzed by **8 a** (Table 3 and 4). Therefore, neither the relative concentrations of the minor and major diastereomers, nor the presence of the other compounds in equilibrium with a catalyst-substrate complex affect the stereochemical result of the asymmetric hydrogenation catalyzed by **8 a**.

Of interest are the results obtained for the catalyst-substrate complex **17** derived from **8 a** and dimethyl β,β-dimethyl(α-acetamido)acrylate, since the corresponding catalytic hydrogenation gives poor enantioselectivity. We found that the binding of the substrate was very weak in this case: when a 2-fold excess of the substrate was added to a solution of **8 a** in deuteriomethanol, the ratio **17** : **8 a** was only 1 : 10. This ratio changed to 1 : 25 at –20 °C, and it could not be measured at higher temperatures due to significant broadening of the signals. Only the ^{31}P NMR spectrum of **17** could be reliably measured: δ(P1) = 71.4 ($^{1}J_{Rh,P}$ = 162 Hz), δ(P2) = 72.4, ($^{1}J_{Rh,P}$ = 171 Hz), $^{2}J_{P,P}$ = 32 Hz. Since this substrate gives a very poor ee of the product in catalytic hydrogenation using **5 a** as a catalyst precursor, we conclude that a reasonably strong substrate binding may be an important factor for the successful asymmetric hydrogenation.

Monohydride Intermediates

The monohydride intermediates **18 a–c** and **19** were generated either by the reaction of solvate dihydrides **8 a–c** with the corresponding substrates at –100 °C, or by hydrogenation of the catalyst-substrate complexes **13 a–c** and **17** at –80 °C. The main hydride component of the reaction mixture was the same when either of these techniques was used. The reaction of the dihydride with the substrate proceeded more cleanly, but the alternative methodology afforded higher concentrations of the monohydride intermediates if longer reaction times (1 h) were applied. The NMR data for the monohydride intermediates **18 a–c** are given in Table 9.



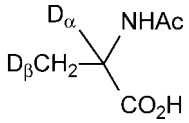
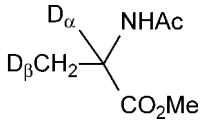
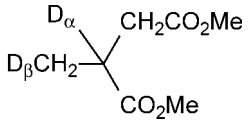
9a-c **18a-c, 19**

18a: R = *t*-Bu, R^1 = Ph, R^2 = H
18b: R = Ad, R^1 = Ph, R^2 = H,
18c: R = 1-Methylcyclohexyl, R^1 = Ph, R^2 = H
19: R = *t*-Bu, R^1 = Me, R^2 = Me

Scheme 5

We found that the isomeric ratio of the observed monohydride intermediates corresponds to the optical yields observed in the catalytic asymmetric hydrogenation. Thus, the reactions of **9 a–c** with methyl (*Z*)-α-acetamidocinnamate give exclusively single isomers of corresponding monohydride intermediates **18 a–c**, whereas the reaction of **9 a** with dimethyl (β,β-dimethyl)acrylate, or low-temperature hydrogenation of the catalyst-substrate complex **17** gave four signals in the hydride region of the ^{1}H NMR spectrum at δ = –21.5, –21.9, –22.7, and –23.0 in a ratio 1.0 : 1.4 : 0.4 : 0.3, attributable to four different isomers of corresponding monohydride intermediate. Unfortunately, only very low concentrations of these intermediates could be obtained due to the weak binding of this substrate (see above), and their structures re-

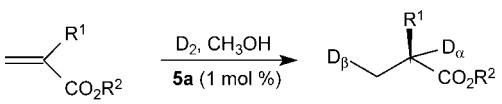
Table 10. Results of the deuteration experiments for *N*-acetylaminoacrylic acid, methyl *N*-acetylaminoacrylate, and dimethyl itaconate

Product	Ratio Dα:Dβ from ^{2}H NMR	Ratio $COCH_3$:CH_2D from ^{1}H NMR	Detection of monodeuterated product in ^{13}C NMR
	1.00:1.03	3.00:2.05	Not detected
	1.00:1.02	3.00:2.04	Not detected
	1.00:1.00	3.01:2.00	Not detected

main unclear. Nevertheless, the pairwise ratio of these isomers compared to the ee obtained from catalytic hydrogenation shows that an apparent correlation does exist. This suggests that two major components of the mixture of isomers **19** give *R*-product, and two minor isomers produce the *S*-amino acid. One obtains an optical yield of 55% at the stage of the monohydride intermediates; the same ee value was obtained after quenching the reaction in an NMR tube, as well as in catalytic hydrogenation (Table 3). If this conclusion is correct, it means that the migratory insertion step is an irreversible and stereodetermining step. This suggestion is in accord with recent computational results of Landis et al.[59] To check further the reversibility of migratory insertion, we carried out deuteration experiments.

Deuteration Studies

An analysis of the products of catalytic deuteration allows us to check the reversibility of the reductive elimination step, since in the case of a reversible reductive elimination one should expect an unequal distribution of deuterium between two sites.[60, 61] Our experimental data support the conclusion that the reductive elimination step of the asymmetric hydrogenation catalyzed by *t*-Bu-BisP* catalyst is irreversible. The experimentally observed deuterium distribution checked by ^{1}H, ^{2}H, and ^{13}C NMR spectroscopy in all studied cases attested for the complete absence of deuterium scrambling (Table 9).



R^1 = NHAc, R^2 = H;
R^1 = NHAc, R^2 = Me
R^1 = CH_2CO_2Me, R^2 = Me

Scheme 6.

Interestingly, we have obtained these results by carrying out the deuterations in methanol. Previous workers reported that considerable scrambling was observed in methanol when the Rh(I) DIPHOS complex was used as a catalyst, and only the use of inert solvents, such as CH_2Cl_2 or THF eliminated this problem.[60,61] The thermal stabilities of the monohydride intermediate produced from DIPHOS[62] and **18a**[38] seem to be almost the same. Therefore, the lack of a similar scrambling in our case suggests that the hydride (deuteride) is more strictly bound to Rh in **18a** and does not react with methanol.

Thus, both the isomeric composition of the monohydride intermediates and the deuteration studies testify for the irreversible migratory insertion step, whereas the stability of solvate dihydrides **9** imply that all stages before the migratory insertion are reversible. These facts taken together make it possible to conclude that the migratory insertion is a stereodetermining step in the asymmetric hydrogenation catalyzed by BisP* catalysts. Following the early suggestion of Seebach,[63] we have recently suggested the mechanism for stereoselection oi the migratory insertion step.[38] In this mechanism, the main stereoregulating factor is the minimization of the steric repulsion in the unstable dihydride intermediate (e. g., **10** in Scheme 3) between the chelate ring made by the substrate and one of the alkyl groups of the ligand (e. g., the favorable intermediate **10** is depicted in Scheme 3, the chelate cycle is *cis* to the methyl group, which corresponds to the observed *R*-stereoselection). All new experimental facts reported here are in accord with this mechanism of stereoselection.

Conclusions

New rhodium(I) complexes containing the P-chirogenic diphosphine ligands BisP* (**1**) and MiniPHOS (**2**) are among the most effective catalysts for the hydrogenation of dehydroamino acids and itaconic acid derivatives known today. The straightforward preparation of the catalytic precursors, the high optical yields observed for a wide series of substrates together with the high catalytic activity make them appropriate for extensive practical applications. The properties of the catalyst may be tuned by changing the nature of the bulky alkyl group in the catalytic precursor; however, the combination of *t*-Bu-BisP* and *t*-Bu-MiniPHOS is sufficient to provide the best known enantioselectivities for almost all substrates reported here. The electronic properties of the Rh(I) complexes of BisP* and MiniPHOS ligands stipulate the relative stability of the solvate dihydrides. However, the possibility for the dihydride mechanism does not interfere in the stereoselection, since the enantioselectivity is determined on the later stage, viz., the migratory insertion step.

Studies on the further synthetic applications of BisP* and MiniPHOS ligands are underway in our laboratory.

Experimental Section

General Procedures

All reactions and manipulations were performed under dry argon atmospheres using standard Schlenk-type techniques. Solvents were purified appropriately before use. Melting points were determined in open capillaries using a Yamato micro melting point apparatus and were not corrected. ^{1}H, ^{13}C, ^{31}P, and ^{11}B NMR spectra were recorded using JEOL LA-400, LA-500, and LA-600 instruments. Optical rotations were measured with a JASCO DIP-370 digital polarimeter with 1-dm-long cells. Enantiomeric excesses were determined by HPLC analysis performed on a Hitachi L-6000 pump and Hitachi L-4000 UV detector with an appropriate chiral column, or by capillary GC analysis with a Chrompack's Chiral-L-Val column.

General Procedure for the Synthesis of Alkyl(dimethyl)-phosphine-Boranes 4 a–g

To a stirred solution of phosphorus trichloride (0.1 mol) in THF (100 mL) was slowly added a 1.0 M THF solution of the corresponding RMgX (0.11 mol) at –78 °C under an Ar atmosphere over a period of 2 h, and the mixture was allowed to warm to room temperature. After the mixture was stirred for 1 h, the flask was immersed in an ice-bath and methylmagnesium chloride (240 mL of a 1.0 M THF solution, 0.24 mol) was added over 30 min. The ice-bath was removed and the mixture was stirred for 1 h at ambient temperature. The flask was again immersed in an ice-bath and BH_3-THF complex (150 mL of a 1.0 M THF solution, 0.15 mol) was added. One hour later, the reaction mixture was slowly added to vigorously stirred ice-water (ca. 400 mL) containing 50 mL of conc. HCl. The organic layer was separated and the aqueous layer was extracted with EtOAc (3×150 mL). The combined extracts were washed with brine, dried over Na_2SO_4, and evaporated under reduced pressure.

***t*-Butyl(dimethyl)phosphine-Borane (4 a)**

Purified by sublimation in vacuum at approximately100 °C (1 mm Hg), yield: 94%. Further purification by recrystallization from hexane afforded pure compound: mp 164–166 °C; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.45 (dq, 3H, BH_3, $^{1}J_{H,B}$ = 95 Hz, $^{2}J_{H,P}$ = 15 Hz), 1.16 (d, 9H, 3 CH_3, $^{3}J_{P,H}$ = 14 Hz), 1.23 (d, 6H, 2 CH_3, $^{2}J_{P,H}$ = 10 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 7.27 (d, 2 CH_3, $^{1}J_{C,P}$ = 35 Hz), 26.63 (C_{tert}, $^{1}J_{C,P}$ = 35 Hz), 30.30 (3 CH_3); ^{31}P NMR (202 MHz, $CDCl_3$, 298 K): δ = 21.5 (q, $^{1}J_{P,B}$ = 63 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –57.3 (d, $^{1}J_{B,P}$ = 63 Hz); FAB MS (*m*/z): 131 (M^+ – H), 118 (M^+ – BH_3).

***1*-Adamantyl(dimethyl)phosphine-Borane (4 b)**

Purified by recrystallization from ethyl acetate, yield: 40%, mp 153–155 °C; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.45 (br q, 3H, BH_3, $^{1}J_{H,B}$ = 94 Hz), 1.17 (d, 6H, 2 CH_3, $^{2}J_{P,H}$ = 10 Hz), 1.67–1.82 (m, 12H), 2.08 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 5.77 (d, 3 CH_3, $^{1}J_{C,P}$ = 40 Hz), 24.68 (3 CH_2, $^{2}J_{C,P}$ = 3 Hz), 29.33 (C_{tert}, $^{1}J_{C,P}$ = 35 Hz), 35.38, 36.40 (3 CH_2); HRMS calcd for $C_{12}H_{25}PB$ 209.1631, found 209.1649.

***1*-Methylcyclohexyl(dimethyl)phosphine-Borane (4 c)**

Overnight stirring at room temperature was applied after addition of methylmagnesium chloride. Purified by distillation in vacuum, bp 84–86 °C (2 torr), yield: 71%; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.40 (br. q, 3H, BH_3), 1.19 (d, 6H, 2 CH_3, $^{3}J_{P,H}$ = 15 Hz), 1.28 (d, 3H, CH_3, $^{2}J_{P,H}$ = 10 Hz), 1.40–1.65 (m, 9H of cyclohexyl), 1.73 (br.d, 1H of cyclohexyl); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 6.47 (d, 2 CH_3, $^{1}J_{C,P}$ = 35 Hz), 16.48 (CH_3), 20.48 (2 CH_2, $^{2}J_{C,P}$ = 10 Hz), 25.57 (CH_2), 29.43 (C_{tert}, $^{1}J_{C,P}$ = 36 Hz), 30.30 (2 CH_2); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 22.0 (q, $^{1}J_{P,B}$ = 62 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –62.1 (d, $^{1}J_{B,P}$ = 62 Hz); FAB MS (*m*/z): 169 (M^+ – 3H).

***1,1*-Diethylpropyl(dimethyl)phosphine-Borane (4 d)**

Overnight stirring at room temperature was applied after addition of methylmagnesium chloride. Purified by chromatography on silica gel (hexane–EtOAc, 20 : 1); yield: 47%; mp 92–94 °C; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.57 (br q, 3H, BH_3, $^{1}J_{H,B}$ = 109 Hz), 0.96 (t, $^{3}J_{H,H}$ = 8 Hz), 1.30 (d, 6H, 2 CH_3, $^{2}J_{P,H}$ = 10 Hz), 1.64 (dq, 6H, 3 CH_2, $^{3}J_{P,H}$ = 14 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 8.91 (3 CH_3), 10.69 (d, 2 CH_3, $^{1}J_{C,P}$ = 35 Hz), 26.38 (3 CH_2, $^{2}J_{C,P}$ = 3 Hz), 36.09 (C_{tert}, $^{1}J_{C,P}$ = 30 Hz); FAB MS (*m*/z): 171 (M^+ – 3H), 160 (M^+ – BH_3).

***Cyclopentyl*(dimethyl)phosphine-Borane (4 e)**

Purified by distillation in vacuum; bp 88–90 °C (1 torr); yield: 70%; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.42 (br. q, 3H, BH_3, $^{1}J_{B,H}$ = 95 Hz), 1.26 (d, 6H, 2 CH_3, $^{2}J_{P,H}$ = 10 Hz), 1.53–2.05 (m, 9H of cyclopentyl); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 9.5–10.2 (m, 2 CH_3), 26.28 (2 CH_2, $^{2}J_{C,P}$ = 9 Hz), 27.07 (2 CH_2), 34.63 (CH, $^{1}J_{C,P}$ = 39 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 10.3 (q, $^{1}J_{P,B}$ = 62 Hz); ^{11}B NMR (128 MHz,

$CDCl_3$, 298 K): δ = –62.3 (d, $^1J_{B,P}$ = 62 Hz); EI MS (*m*/z): 141 (M^+ – 3 H), 130 (M^+ – BH_3).

Cyclohexyl(dimethyl)phosphine-Borane (4 f)
Purified by distillation in vacuum; bp 72–73 °C (1 torr); yield: 66%; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.41 (br. q, 3 H, BH_3, $^1J_{B,H}$ = 94 Hz), 1.23 (d, 6 H, 2 CH_3, $^2J_{P,H}$ = 10 Hz), 1.15–1.95 (m, 11 H of cyclohexyl); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 8.47 (d, 2 CH_3, $^1J_{C,P}$ = 37 Hz), 25.68 (2 CH_2, $^3J_{C,P}$ = 2 Hz), 25.87 (2 CH_2), 26.30 (2 CH_2, $^2J_{C,P}$ = 12 Hz), 34.33 (CH, $^1J_{C,P}$ = 36 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 9.7 (q, $^1J_{P,B}$ = 65 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –61.6 (d, $^1J_{B,P}$ = 65 Hz); FAB MS (*m*/z): 155 (M^+ – 3 H), 144 (M^+ – BH_3).

Isopropyl(dimethyl)phosphine-Borane (4 g)
Purified by sublimation in vacuum at ca. 100 °C (1 torr); yield: 49%; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.42 (br. q, 3 H, BH_3, $^1J_{B,H}$ = 96 Hz), 1.15–1.19 (2, 6 H, 2 CH_3), 1.25 (d, 6 H, 2 CH_3, $^2J_{H,P}$ = 10 Hz), 1.85 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 8.68 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 16.18 (d, 2 CH_3, $^3J_{C,P}$ = 10 Hz), 26.03 (d, 2 CH_2, $^1J_{C,P}$ = 30 Hz); HRMS calcd. for $C_5H_{15}PB$ 117.1005, found 117.1000.

General Procedure for the Synthesis of 1,2-Bis(boronato-(alkyl)methylphosphino)ethanes 3 a–g
To a stirred, cooled (–78 °C) solution of (–)-sparteine (16 mmol) in Et_2O (50 mL) was added *s*-BuLi (18 mL of a 0.95 M hexane solution, 16 mmol) under an Ar atmosphere. After 10 min, a solution of the corresponding alkyl(dimethyl)phosphine–borane (13 mmol) in Et_2O was added dropwise, and the mixture was stirred at –78 °C. Five hours later, dry $CuCl_2$ (2.6 g, 20 mmol) was added in one portion with vigorous stirring, and the mixture was gradually warmed to room temperature during 2 h. After stirring for an additional 1 h the reaction was quenched by the addition of 25% aqueous ammonia (30 mL). The organic layer was separated and the aqueous layer was extracted either with ethyl acetate (in the case of compounds **3 a** and **3 d–g**) or with chloroform (compounds **3 b, c**). The combined organic layers were washed with 5% NH_4OH, 2 M HCl, and brine, and then dried over Na_2SO_4. The solvent was removed on an evaporator to leave white residue, which was further purified (see below).

(S,S)-1,2-Bis(boranato(t-butyl)methylphosphino)ethane 3 a
Recrystallization of the crude product from toluene afforded the pure product; yield: 40%; mp 169–171 °C; $[\alpha]_D^{27}$: –9.1 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.39 (br. q, 6 H, 2 BH_3, $^1J_{H,B}$ = 99 Hz), 1.18 (d, 18 H, 6 CH_3, $^3J_{H,P}$ = 14 Hz), 1.22 (d, 6 H, 2 CH_3, $^2J_{H,P}$ = 10 Hz), 1.57–1.66 (m, 2 H, CH_2), 1.96–2.04 (m, 2 H, CH_2); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 5.55 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 15.87 (d, 2 CH_2, $^1J_{C,P}$ = 31 Hz), 25.10 (6 CH_3), 27.56 (2 C_{tert}, $^1J_{C,P}$ = 34 Hz), ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 29.8 (q, $^1J_{P,B}$ = 65 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –64.1 (d, $^1J_{B,P}$ = 65 Hz); FAB MS (*m*/z): 263 (M^+ + H), 247 (M^+ – BH_3–H).

(S,S)-1,2-Bis(boranato(1-adamantyl)methylphosphino)-ethane 3 b
Recrystallization of the crude product from toluene afforded pure product; yield: 33%; mp 285 °C (decomp); $[\alpha]_D^{27}$: +5.3 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.0–0.8 (br. q, 6 H, 2 BH_3, $^1J_{H,B}$ = 108 Hz), 1.15 (d, 6 H, 2 CH_3, $^2J_{H,P}$ = 9 Hz), 1.67–1.92 (m, 22 H of adamantyl, CH_2), 2.05 (m, 4 H of adamantyl, CH_2); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 4.25 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 14.27 (d, 2 CH_2, $^1J_{C,P}$ = 31 Hz), 27.54 (d, 2 CH_2, $^2J_{C,P}$ = 8 Hz), 30.46 (2 C_{tert}, $^1J_{C,P}$ = 34 Hz), 35.9 (2 CH_2), 36.4 (2 CH_2); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 25.1 (q, $^1J_{P,B}$ = 71 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –64.7 (d, $^1J_{B,P}$ = 71 Hz); HRMS calcd. for $C_{24}H_{45}P_2B_2$ 417.3182, found 417.3176.

(S,S)-1,2-Bis(boranato(1-methylcyclohexyl)methyl-phosphino)ethane 3 c
Optically pure product was obtained by recrystallization of crude material from toluene; yield: 41%; mp 204–205 °C; $[\alpha]_D^{25}$: –6.4 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.0–0.8 (br. q, 6 H, 2 BH_3), 1.2 (m, 14 H, 4 CH_3 + 2 H of cyclohexyl), 1.55 (m, 18 H of cyclohexyl, CH_2), 1.72 (br. d, 2 H of cyclohexyl), 2.0 (m, 2 H of cyclohexyl); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 4.85 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 15.07 (d, 2 CH_2, $^1J_{C,P}$ = 30 Hz), 16.85 (2 CH_3), 20.48 (m, 2 CH_2), 25.56 (CH_2), 30.74 (d, 2 CH_2, $^2J_{C,P}$ = 10 Hz), 30.76 (2C_{tert}, $^1J_{C,P}$ = 34 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 30.9 (q, $^1J_{P,B}$ = 54 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –64.2 (d, $^1J_{B,P}$ = 62 Hz); FAB MS (*m*/z): 343 (M^+ + H), 327 (M^+ – CH_3).

(S,S)-1,2-Bis(boranato(1,1-diethylpropyl)methyl-phosphino)ethane 3 d
Optically pure product was obtained by flash chromatography of crude material on silica gel (hexane-EtOAc, 20 : 1), followed by recrystallization from methanol; yield: 69%; mp 132–133 °C; $[\alpha]_D^{25}$: –19.5 ° (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.52 (br. q, 6 H, 2 BH_3, $^1J_{H,B}$ = 102 Hz), 0.97 (t, 18 H, 6 CH_3, $^3J_{H,H}$ = 8 Hz), 1.29 (d, 6 H, $^2J_{H,P}$ = 9 Hz), 1.61–1.72 (m, 14 H), 2.10–2.23 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 8.5–9.0 (m, 8 CH_3), 18.03 (d, 2 CH_2, $^1J_{C,P}$ = 30 Hz), 26.4–26.7 (3 CH_3), 37.54 (2 C_{tert}, $^1J_{C,P}$ = 28 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 27.4 (q, $^1J_{P,B}$ = 68 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –61.0 (d, $^1J_{B,P}$ = 52 Hz); FABMS (*m*/z): 345 (M^+ – H), 331 (M^+ – BH_3 – H); anal. Calcd. for $C_{18}H_{46}B_2P_2$: C, 62.46; H, 13.39. Found: C, 62.86; H, 13.38.

(S,S)-1,2-Bis(boranato(cyclopentyl)methylphosphino)-ethane 3 e
Optically pure product was obtained by flash chromatography of crude material on silica gel (hexane–EtOAc, 20 : 1), followed by recrystallization from 2-propanol; yield: 34%; mp 120–121 °C; $[\alpha]_D^{26}$: –10.6° (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.36 (br. q, 6 H, 2 BH_3, $^1J_{H,B}$ = 98 Hz), 1.25 (d, 6 H, 2 CH_3 $^2J_{H,P}$ = 10 Hz), 1.53–2.10 (m, 22 H); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 7.4 (d, 2 CH_3, $^1J_{C,P}$ = 36 Hz), 26.25 (m, 4 CH_2,), 26.45 (m, 4 CH_2), 33.54 (2 CH, $^1J_{C,P}$ = 37 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 20.3 (q, $^1J_{P,B}$ = 71 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –63.9 (d, $^1J_{B,P}$ = 71 Hz); FABMS (*m*/z): 283 (M^+ – 3 H), 271 (M^+ – BH_3 – H); HRMS calcd. for $C_{14}H_{31}B_2P_2$: 283.2092, found 283.2094.

(S,S)-1,2-Bis(boranato(cyclohexyl)methylphosphino)-ethane 3 f
Optically pure product was obtained by recrystallization from toluene; yield: 55%; mp 179–182 °C; $[\alpha]_D^{26}$: +2.1 ° (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.40 (br. q, 6 H, 2 BH_3,

$^1J_{H,B}$ = 103 Hz), 1.22 (d, 6 H, 2 CH_3 $^2J_{H,P}$ = 10 Hz), 1.20–2.00 (m, 26 H); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 6.1 (d, 2 CH_3, $^1J_{C,P}$ = 36 Hz), 16.35 (d, 2 CH_2, $^1J_{C,P}$ = 32 Hz), 25.65, 26.0, 26.2, 26.4–26.6 (CH_2 from cyclohexyl), 33.14 (d, 2 CH, $^1J_{C,P}$ = 34 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 19.2 (q, $^1J_{P,B}$ = 52 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –63.5 (d, $^1J_{B,P}$ = 52 Hz); FABMS (*m*/z): 313 (M^+ – 3 H), 299 (M^+ – BH_3 – H).

(S,S)-1,2-Bis(boranato(isopropyl)methylphosphino)-ethane 3 f

Product of 80% optical purity was obtained by multiple recrystallization from methanol; mp 84–85 °C; $[\alpha]_D^{26}$: –5.6° (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.42 (br. q, 6 H, 2 BH_3, $^1J_{H,B}$ = 99 Hz), 1.25 (m, 18 H, 6 CH_3), 1.50–2.00 (m, 6 H, 2 CH_2, 2 CH); ^{13}C NMR (100 MHz, $CDCl_3$, 298 K): δ = 5.78 (d, 2 CH_3, $^1J_{C,P}$ = 36 Hz), 16.29 (d, 4 CH_3, $^2J_{C,P}$ = 15 Hz), 16.72 (d, 2 CH_2, $^1J_{C,P}$ = 32 Hz), 23.25 (d, 2 CH, $^1J_{C,P}$ = 35 Hz); ^{31}P NMR (161 MHz, $CDCl_3$, 298 K): δ = 23.0 (q, $^1J_{P,B}$ = 58 Hz); ^{11}B NMR (128 MHz, $CDCl_3$, 298 K): δ = –63.7 (d, $^1J_{B,P}$ = 58 Hz); FABMS (*m*/z): 231 (M^+ – 3 H), 219 (M^+ – BH_3 – H).

Enantiomeric Excess Determination

The enantiomeric purity of diphosphine–boranes **3 a–f** was determined by HPLC analysis (Daicel Chiracel OD-H, 10% 2-PrOH/hexane): **3 a**: 0.5 mL/min, (*R,R*) t_1 = 10.2 min, (*S,S*) t_2 = 14.2 min; **3 d**: 0.5 mL/min, (*R,R*) t_1 = 9.7 min, (*S,S*) t_2 = 10.6 min; **3 e**: 1.0 mL/min, (*R,R*) t_1 = 10.2 min, (*S,S*) t_2 = 14.2 min; **3 f**: 0.5 mL/min, (*R,R*) t_1 = 12.8 min, (*S,S*) t_2 = 16.8 min.

General Procedure for the Preparation of Diphosphines 1 a–g

Trifluoromethanesulfonic acid (840 µL, 9.5 mmol) was slowly added to a stirred, cooled (0 °C) solution of (*S,S*)-1,2-bis(boranato(alkyl)methylphosphino)ethane (1.9 mmol). After 30 min the ice bath was removed and the reaction mixture was stirred at room temperature until the disappearance of bisphosphine-borane (TLC control). The solvent was removed in vacuo. A solution of KOH (1.07 g, 19 mmol) in 7.7 mL of EtOH–H_2O (10 : 1) was slowly added with stirring to the resulting pasty oil. The reaction mixture was stirred at 50 °C for 2 h and cooled to room temperature and extracted three times with ether. The combined extracts were dried over Na_2SO_4 and the solution was passed through a column of basic alumina (30 g). The solvent was removed in vacuo producing practically pure diphosphine (oil or easily melting crystals).

(S,S)-1,2-Bis(t-butylmethylphosphino)ethane 1 a

Yield: 96%; ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): δ = 0.92 (m, 6 H, 2 CH_3), 1.00 (m, 18 H, 6 CH_3), 1.21 (m, 2 H) and 1.54 (m, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): δ = 6.7 (2 CH_3, m, 4 intensive lines at δ = 6.78, 6.84, 6.88, 6.94), 21.9 (2 CH_2, m, 5 lines at δ = 21.65, 21.89, 21.91, 21.95, 22.23), 26.7 (6 CH_3, m, 3 intensive lines at δ = 26.78, 26.84, 26.89), 27.0 (C_{tert}, m, 4 intensive lines at δ = 27.12, 27.15, 27.16, 27.19); ^{31}P NMR (202 MHz, $CDCl_3$, 25 °C): δ = –9.67.

General Procedure for the Preparation of Catalytic Precursors 5 a–g

A solution of corresponding (*S,S*)-1,2-bis(alkylmethylphosphino)ethane (1.8 mmol) in freshly distilled THF (10 mL) was added to a stirred suspension of $[Rh(nbd)_2]BF_4$ (622 mg, 1.8 mmol) in THF (15 mL). The suspension gradually turned to an almost clear solution during 2 h. It was filtered and the solvent was removed in vacuo. The residual solid was washed with hexane to give an orange powder, which was dried in vacuo.

[(1 a)Rh(nbd)]BF$_4$ 5 a

Pure compound was obtained by recrystallization from a small amount of THF; yield: 54%; ^{1}H NMR (500 MHz, CD_3OD, 298 K): δ = 1.10 (18 H, 6 CH_3, $^3J_{H,P}$ = 13.0 Hz), 1.39 (d, 6 H, 2 CH_3, $^2J_{H,P}$ = 7.6 Hz), 1.55 (m, 2 H of CH_2CH_2), 1.84 (br. s, 2 H, CH_2 from norbornadiene), 1.99 (m, 2 H of CH_2CH_2), 4.18 (br. s, 2 H, 2 CH of norbornadiene), 5.77 and 5.78 (2 br. s, 4 H, 2 CH=CH from norbornadiene); ^{13}C NMR (125 MHz, CD_3OD, 25 °C): δ = 5.81 (m, 6 lines, 2 CH_3), 21.27 (m, 7 lines, 2 CH_2), 26.26 (s, 6 CH_3), 32.36 (m, 5 lines, 2 C_{tert}), 56.49 (s, CH_2 from norbornadiene), 72.13 (dt, 2 CH from norbornadiene, $J_{C,Rh}$ = 3.9 Hz, J_{CP} = 1.8 Hz), 84.85 (dt, 2 CH=, $J_{C,Rh}$ = 5.2 Hz, $J_{C,P}$ = 4.1 Hz), 89.39 (dt, 2 CH=, $J_{C,Rh}$ = 5.2 Hz, $J_{C,P}$ = 4.1 Hz); ^{31}P NMR (202 MHz, $CDCl_3$, 25 °C): δ = 62.66 (d, $^1J_{P,Rh}$ = 151.8 Hz).

[(1 b)Rh(nbd)]BF$_4$ 5 b

Pure compound was obtained by recrystallization from a small amount of THF; ^{1}H NMR (400 MHz, CD_3OD, 298 K): δ = 1.34 (6 H, 2CH_3, $^3J_{H,P}$ = 17.6 Hz), 1.52 (m, 2 H from adamantyl), 1.69 (m, 6 H from adamantyl), 1.75–190 (m, 16 H from adamantyl, CH_2 from norbornadiene), 2.02 (m, 2 H from adamantyl, 4 H of CH_2CH_2), 4.19 (br. s, 2 H, 2 CH of norbornadiene), 5.75 and 5.84 (2 br.s, 4 H, 2 CH=CH from norbornadiene); ^{13}C NMR (100 MHz, CD_3OD, 25 °C): δ = 4.06 (m, 2 CH_3), 19.40 (2 CH_3), 29.40 (m, 2 CH_2), 36.05 (m, 2 C_{tert}), 37.52 (2 CH_2), 38.26 (2 CH) 56.66 (2 CH from norbornadiene), 72.30 (m, CH_2 from norbornadiene), 84.33 (m, 2 CH=), 89.42 (m, 2 CH=); ^{31}P NMR (162 MHz, $CDCl_3$, 25 °C): δ = 56.16 (d, $^1J_{P,Rh}$ = 151.0 Hz).

[(1 c)Rh(nbd)]BF$_4$ 5 c

Pure complex was obtained by recrystallization from THF; ^{1}H NMR (400 MHz, CD_3OD, 298 K): δ = 1.19 (6 H, 2 CH_3, $^3J_{H,P}$ = 17.6 Hz), 1.24 (m, 2 H from cyclohexyl), 1.38 (d, 6 H, 2 CH_3, $^2J_{H,P}$ = 8.3 Hz), 1.55 (m, 16 H from cyclohexyl), 1.73 (br. d, 2 H from cyclohexyl), 1.82 (br.s, 2 H, CH_2 from norbornadiene), 1.99 (m, 4 H of CH_2CH_2), 4.18 (br. s, 2 H, 2 CH of norbornadiene), 5.71 and 5.74 (2 br.s, 4 H, 2 CH=CH from norbornadiene); ^{13}C NMR (100 MHz, CD_3OD, 25 °C): δ = 4.89 (m, 2 CH_3), 18.50 (2 CH_3), 21.66 (m, 2 CH_2), 21.79 (m, 2 CH_2), 26.77 (2 CH_2), 32.76 (2 CH_2), 33.74 (2 CH_2), 35.82 (m, 2 C_{tert}), 56.46 (2 CH from norbornadiene), 72.13 (m, CH_2 from norbornadiene), 84.39 (m, 2 CH=), 88.99 (m, 2 CH=); ^{31}P NMR (162 MHz, $CDCl_3$, 25 °C): δ = 63.72 (d, $^1J_{P,Rh}$ = 152.0 Hz); FABMS (*m/z*): 415 ([BisP*Rh]$^+$ + H_2).

[(1 e)Rh(nbd)]BF$_4$ 5 e

^{1}H NMR (400 MHz, CD_3OD, 298 K): δ = 1.34 (6 H, 2 CH_3, $^3J_{H,P}$ = 17.6 Hz), 1.43 (m, 2 H from cyclopentyl), 1.50–1.65 (m, 12 H from cyclopentyl), 1.72 (s, 2 H from norbornadiene), 1.75–1.95 (m, 6 H, 2 CH_2, 2 H from cyclopentyl), 2.11 (m, 2 H from cyclopentyl), 4.06 (br. s, 2 H, 2 CH of norbornadiene), 5.52 and 5.59 (2 br. s, 4 H, 2 CH=CH from norbornadiene); ^{13}C NMR (100 MHz, CD_3OD, 25 °C): δ = 8.51 (m, 2 CH_3), 24.34 (m, 2 CH_2), 27.25 (m, 2 CH_2), 27.58 (m, 2 CH_2),

29.52 (m, 4 CH_2), 37.51 (m, 2 C_{tert}), 57.21 (2 CH from norbornadiene), 72.15 (m, CH_2 from norbornadiene), 88.31 (m, 2 CH=), 89.75 (m, 2 CH=); ^{31}P NMR (162 MHz, $CDCl_3$, 25 °C): δ = 53.00 (d, $^1J_{P,Rh}$ = 155.0 Hz).

[(1f)Rh(nbd)]BF$_4$ 5f

^{1}H NMR (400 MHz, CD_3OD, 298 K): δ = 0.95 (t, 2 H from cyclohexyl), 1.25–1.50 (m, 16 H, 2 CH_3, 10 H from cyclohexyl), 1.75–2.05 (m, 16 H, 2 CH_2, 10 H from cyclohexyl, CH_2 from norbornadiene), 4.09 (br. s, 2 H, 2 CH of norbornadiene), 5.59 and 5.65 (2 br.s, 4 H, 2 CH=CH from norbornadiene); ^{13}C NMR (100 MHz, CD_3OD, 25 °C): δ = 8.51 (m, 2 CH_3), 22.77 (m, 2 CH_2), 27.25 (m, 2 CH_2), 27.58 (m, 2 CH_2), 29.52 (m, 4 CH_2), 37.34 (m, 2 C_{tert}), 57.21 (2 CH from norbornadiene), 72.15 (m, CH_2 from norbornadiene), 88.31 (m, 2 CH=), 89.75 (m, 2 CH=); ^{31}P NMR (162 MHz, $CDCl_3$, 25 °C): δ: 53.60 (d, $^1J_{P,Rh}$ = 155.0 Hz).

[(1g)Rh(nbd)]BF$_4$ 5g

^{1}H NMR (400 MHz, CD_3OD, 298 K): δ = 0.95 (t, 2 H from cyclohexyl), 1.25–1.50 (m, 16 H, 2 CH_3, 10 H from cyclohexyl), 1.75–2.05 (m, 16 H, 2 CH_2, 10 H from cyclohexyl, CH_2 from norbornadiene), 4.09 (br. s, 2 H, 2 CH of norbornadiene), 5.59 and 5.65 (2 br.s, 4 H, 2 CH=CH from norbornadiene); ^{13}C NMR (100 MHz, CD_3OD, 25 °C): δ = 8.51 (m, 2 CH_3), 22.77 (m, 2 CH_2), 27.25 (m, 2 CH_2), 27.58 (m, 2 CH_2), 29.52 (m, 4 CH_2), 37.34 (m, 2 C_{tert}), 57.21 (2 CH from norbornadiene), 72.15 (m, CH_2 from norbornadiene), 88.31 (m, 2 CH=), 89.75 (m, 2 CH=); ^{31}P NMR (162 MHz, $CDCl_3$, 25 °C): δ = 57.9 (d, $^1J_{P,Rh}$ = 154 Hz).

General Procedure for the Synthesis of (*R,R*)-Bis(boranato(alkyl)methylphosphino)methanes 6 a–d

To a stirred, cooled (–78 °C) solution of (–)-sparteine (5.64 g, 24 mmol) in Et_2O (20 mL) was added *s*-BuLi (25 mL of a 0.97 M cyclohexane solution, 24 mmol) under an argon atmosphere. After 10 min, corresponding alkyl(dimethyl)-phosphine–borane **4** (20 mmol) was added in one portion, and the mixture was stirred at –78 °C. Five hours later, this solution was added dropwise to a solution of the corresponding alkyldichlorophosphine (20 mmol) in ether (20 mL) at –78 °C, and the mixture was gradually warmed to room temperature. Methylmagnesium bromide (20 mL of a 1.0 M THF solution, 20 mmol) was added at 0 °C, followed by addition of BH_3-THF (70 mL of a 1 M THF solution, 70 mmol). The reaction was quenched by addition of water. The organic layer was separated and the aqueous layer was extracted with ethyl acetate three times. The combined organic layers were washed with brine, and then dried over Na_2SO_4. The solvent was removed on an evaporator to leave a white residue, which was recrystallized from MeOH to give the enantiomerically pure diphosphine-borane.

(R,R)-Bis(boranato(t-butyl)methylphosphino)methane 6 a

Yield: 22%; mp 188–190 °C; $[\alpha]_D^{14}$: –4.7°(*c* 0.93, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$, 298 K): δ = 0.55 (br.q, 6 H, 2 BH_3), 1.18 (d, 18 H, 6 CH_3, $^3J_{H,P}$ = 14 Hz), 1.54 (d, 6 H, 2 CH_3 $^2J_{H,P}$ = 10 Hz), 1.77 (m, 2 H, CH_2); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): δ = 6.66 (d, 2 CH_3, $^1J_{C,P}$ = 34 Hz), 12.90 (t, CH_2, $^1J_{C,P}$ = 21 Hz), 25.82 (6 CH_3), 29.03 (dd, C_{tert}, $^1J_{C,P}$ = 33 Hz, $^3J_{C,P}$ = 4 Hz); ^{31}P NMR (202 MHz, $CDCl_3$, 25 °C): δ = 28.67 (q, $^1J_{P,B}$ = 53 Hz); ^{11}B NMR (160 MHz, $CDCl_3$, 25 °C): δ = –57.14 (d, $^1J_{P,B}$ = 53 Hz); HRMS: calcd. for $C_{11}H_{29}P_2B_2$ 245.1935, found 245.1932.

(R,R)-Bis(boranato(cyclohexyl)methylphosphino)-methane 6 b

Yield: 19%; mp 135–137 °C; $[\alpha]_D^{14}$: –5.7 ° (*c* 0.96, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.65 (br. q, 6 H, 2 BH_3), 1.17–1.41 (m, 10 H), 1.46 (d, 6 H, $^2J_{H,P}$ = 10 Hz), 1.74–1.88 (m, 14 H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 8.71 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 16.30 (t, CH_2, $^1J_{C,P}$ = 22 Hz), 25.82, 26.00, 26.34, 26.55 (4 CH_2), 35.63 (d, CH, $^1J_{C,P}$ = 39 Hz); HRMS: calcd. for $C_{11}H_{29}P_2B_2$ 297.2249, found 297.2198.

(R,R)-Bis(boranato(isopropyl)methylphosphino)-methane 6 c

Yield: 13%, mp 105–106 °C; $[\alpha]_D^{14}$: –1.0 ° (*c* 0.87, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.62 (br. q, 6 H, 2 BH_3), 1.18 (dd, 12 H, 4 CH_3, $^3J_{H,P}$ = 15 Hz, $^3J_{H,H}$ = 8 Hz,), 1.82 (t, 2 H, CH_2, $^2J_{H,P}$ = 11 Hz,); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 8.75 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 16.22 (d, 4 CH_3, $^3J_{C,P}$ = 12 Hz), 16.41 (t, CH_2, $^1J_{C,P}$ = 21 Hz), 26.02 (dd, 2 CH, $^1J_{C,P}$ = 40 Hz, $^3J_{C,P}$ = 4 Hz); HRMS: calcd. for $C_9H_{25}P_2B_2$ 217.1621, found 297.1630.

(R,R)-Bis(boranato(phenyl)methylphosphino)methane 6 d

Yield: 28%; mp 150–152 °C; $[\alpha]_D^{14}$: –5.1 ° (*c* 1.28, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ = 0.72 (br. q, 6 H, 2 BH_3), 1.84 (d, 6 H, 2 CH_3, $^2J_{H,P}$ = 10 Hz), 2.41 (t, 2 H, CH_2, $^2J_{H,P}$ = 11 Hz,), 7.27–7.56 (m, 10 H, 2 C_6H_5); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 12.71 (d, 2 CH_3, $^1J_{C,P}$ = 35 Hz), 27.12 (d, 4 CH_3, $^3J_{C,P}$ = 24 Hz), 128.71 (d, $^2J_{C,P}$ = 10 Hz), 131.22 (d, $^2J_{C,P}$ = 10 Hz), 131.55 (2 CH), C_{tert} not found; HRMS: calcd. for $C_{15}H_{21}P_2B_2$ 285.1310, found 285.1317.

General Procedure for the Preparation of Diphosphines 2 a–d

Trifluoromethanesulfonic acid (840 µL, 9.5 mmol) was slowly added to a stirred, cooled (0 °C) solution of the corresponding diphosphine-borane **6** (1.9 mmol). After 30 min the ice bath was removed and the reaction mixture was stirred at room temperature until the disappearance of bisphosphine–borane (TLC monitoring). The solvent was removed in vacuo. A solution of KOH (1.07 g, 19 mmol) in 8 mL of EtOH-H_2O (10 : 1) was slowly added with stirring to the resulting pasty oil. The reaction mixture was stirred at 50 °C for 2 h and cooled to room temperature and extracted three times with ether. The combined extracts were dried over Na_2SO_4 and the solution was passed through a column of basic alumina (30 g). The solvent was removed in vacuo producing practically pure diphosphine.

(R,R)-1,1-Bis(t-butylmethylphosphino)methane 2 a

^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): δ = 1.04 (m, 18 H, 6 CH_3), 1.08 (m, 6 H, 2 CH_3), 1.26 (m, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): δ = 9.19 (2 CH_3, m), 22.09 (CH_2, m), 27.92 (6 CH_3, m), 32.27 (C_{tert}, m); ^{31}P NMR (202 MHz, $CDCl_3$, 25 °C): δ = –19.8.

General Procedure for the Preparation of Rh Complexes 7 a–d

A solution of free chiral diphosphine (1.8 mmol) in freshly distilled THF (10 mL) was added to a stirred suspension of $[Rh(nbd)_2]BF_4$ (311 mg, 0.9 mmol) in THF (15 mL). The suspension gradually turned to an almost clear solution during 2 h. It was filtered and the solvent was removed in vacuo. The residual solid was washed with hexane to give the corresponding complex **7** as a yellow powder.

[(R,R)-(MeBu^{t}PCH$_2$PMeBu^t)$_2$Rh]$^+$BF$_4^-$ (7 a)
Yield 67%; ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): δ = 1.49 (m, 6 H, 2 CH_3), 1.22 (m, 18 H, 6 CH_3), 1.49 (m, 6 H, 2 CH_3), 3.26 (m, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): δ = 12.39 (m, 2 CH_3), 26.71 (m, 6 CH_3), 31.99 (m, C_{tert}), 39.55 (m, CH_2); ^{31}P NMR (202 MHz, $CDCl_3$, 25 °C): δ = –23.90 (d, $^1J_{Rh,P}$ = 111 Hz).

General Procedure for Asymmetric Hydrogenation of Dehydroamino Acids
A 50 mL Fisher-Porter tube was charged with the substrate (1 mmol) and the catalyst precursor (0.002 mmol). The tube was connected to the hydrogen tank via stainless steel tubing. The vessel was evacuated and filled with hydrogen gas (Nippon Sanso, 99.9999%) to a pressure of about 2 atm. This operation was repeated and the bottle was immersed in a dry ice-ethanol bath. The upper cock of the bottle was opened and anhydrous and degassed methanol was added quickly using a syringe. After four vacuum/H_2 cycles, the tube was pressurized to a desired initial pressure. The solution or suspension was magnetically stirred at ambient temperature. After completion of hydrogenation the resulting solution was passed through silica gel using ethyl acetate as the eluent, and the filtrate was submitted to direct analysis for the ee values by HPLC or GC.

Enantiomeric Excess Determination
The following list describes conditions used for separation of racemic products: ***N*-acetylphenylalanine methyl ester** (HPLC, Daicel Chiralcel OJ, 1.0 mL/min, hexane/2-propanol = 9/1, (*R*)t_1 = 13.3 min; (*S*)t_2 = 19.3 min); ***N*-acetyl-4-acetoxy-3-methoxyphenylalanine methyl ester** (HPLC, Daicel Chiralcel ODH, 1.0 mL/min, hexane/2-propanol = 9/1, (*R*)t_1 = 13.2 min; (*S*)t_2 = 15.5 min); ***N*-acetylalanine methyl ester** (capillary GC, Chrompack Chiral-Val column (25 m), 120 °C, isothermal, carrier gas: N_2 (flow rate 15 cm/s), (*R*)t_1 = 8.7 min; (*S*)t_2 = 9.7 min); ***N*-acetylvaline methyl ester** (capillary GC, Chrompack Chiral-Val column (25 m), 135 °C, isothermal, carrier gas: N_2 (flow rate 8.5 cm/s), (*R*)t_1 = 10.3 min; (*S*)t_2 = 11.5 min); ***N*-acetyl-α-cyclopentylglycine methyl ester** (capillary GC, Chrompack Chiral-Val column (25 m), 135 °C, isothermal, carrier gas: N_2 (flow rate 5.3 cm/s), (*R*)t_1 = 7.0 min; (*S*)t_2 = 8.1 min); ***N*-acetyl-α-cyclohexylglycine methyl ester** (capillary GC, Chrompack Chiral-Val column (25 m), 135 °C, isothermal, carrier gas: N_2 (flow rate 5.3 cm/s), (*R*)t_1 = 12.4 min; (*S*)t_2 = 13.5 min); ***N*-acetylphenylalanine**, ***N*-acetylalanine**, and ***N*-acetyl-4-acetoxy-3-methoxyphenylalanine** were converted to the corresponding methyl esters by the reaction with diazomethane and their enantiomeric excesses were determined by GC or HPLC.

Solvate Complexes 8 a–c, e
A solution of corresponding catalytic precursor **5** (20 mg) in 0.75 mL of CD_3OD was prepared in a 5-mm NMR tube under argon. Then the sample was degassed by three consequent cycles of freezing, pumping, and warming. The sample was cooled to –20 °C and 2 atm of H_2 were admitted. The sample was intensively shaken manually during the hydrogenation; the temperature was maintained at –20 °C. When the color of the sample changed from orange to pale-yellow, the sample was degassed and 1 atm of argon was admitted. The thus prepared solutions of solvate complexes **8** in deuteriomethanol are stable at ambient temperature.

Dihydride Complexes 9 a–c, e
The solution of a solvate complex **8** in deuteromethanol under hydrogen in a 5-mm NMR tube (see preceding procedure) was cooled to –90 °C and 2 atm of H_2 were admitted. The sample was kept under these conditions for 15 min with intensive manual shaking. Then the sample was placed in the precooled probe of the NMR spectrometer. For the NMR spectra, see Table 5.

Catalyst-Substrate Complexes 13 a–c, 14–17
The solution of solvate complex **9** in deuteriomethanol under argon in a 5-mm NMR tube was cooled to –20 °C and a solution of an equivalent amount of the corresponding substrate in CD_3OD was added. For NMR data, see Table 6–8.

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publications no. CCDC-147411 (**5 b**), CCDC-147780 (**5 c**), CCDC-147410 (**7 a**). The structure of **5 a** was reported previously.[22] Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK fax.: (internat.) + 44 12 23/3 36-0 33; e-mail: deposit@ccdc.cam.ac.uk.

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