JOC Article

Exploring Stereogenic Phosphorus: Synthetic Strategies for Diphosphines Containing Bulky, Highly Symmetric Substituents

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Diphosphine ligands bearing highly symmetric, bulky substituents at a stereogenic P atom were prepared, exploiting established protocols, which include the use of chiral synthons such as 3,4-dimethyl-2,5-diphenyl-1,3,2-oxazaphospholidine-2-borane (**3a**) and phenylmethylchlorophosphine borane (**10**) and the enantioselective deprotonation of dimethylarylphosphine boranes. However, only (Bu^t)(Me)$PCH_2CH_2P(Bu^t)$Me (**8a**) could be prepared from **3a**. The diphosphines (*S*,*S*)-1,2-bis-(mesitylmethylphosphino)ethane, ((*S*,*S*)-**8b**) and (*S*,*S*)-1,2-bis(9-anthrylmethylphosphino)ethane ((*S*,*S*)-**8c**), which contain 2,6-disubstituted aryl P-substituents, were prepared by Evans' sparteine-assisted enantioselective deprotonation of P(Ar)$(Me)_2(BH_3)$ (Ar = mesityl or 9-anthryl), but the enantioselectivity did not exceed 37% ee. The asymmetrically substituted, methylene-bridged diphosphine (2*R*,4*R*)-(Ph)$(CH_3)PCH_2$P(Mes)(CH_3) ((2*R*,4*R*)-**12**) (Mes = mesityl) was prepared by the newly developed stereospecific reaction of the enantiomerically pure chlorophosphine borane PCl(Ph)(Me)(BH_3) (**10**) with the racemic, monolithiated dimethylmesitylphosphine borane P(Mes)-(Me)$(CH_2Li)(BH_3)$. Diastereomerically pure (2*R*,4*R*)-**12** was obtained with 86% ee. The rhodium(I) derivatives [Rh(COD)(P−P)]BF_4 containing the diphosphine ligands **8a**, **8b**, and **12**, as well as the previously reported (*S*,*S*)-1,2-bis(1-naphthylphenylphosphino)ethane ((*S*,*S*)-**8d**), were prepared and tested in the enantioselective catalytic hydrogenation of acetamidocinnamates. The best catalytic result (98.6% ee) was obtained with [Rh(COD)(**8d**)]$^+$ as catalyst and methyl *Z*-α-acetamidocinnamate as substrate. Some of the catalytic results are discussed in terms of the preferred conformations of the substituents at phosphorus, as calculated by molecular modeling.

Introduction

Chiral diphosphines have become an important class of ligands for asymmetric catalysis. It is the success itself of enantioselective catalysis that has enhanced the demand for new chiral ligands for essentially two reasons. The first one is that no class of ligands can be considered as "universal" anymore, as it is linked to a finite, however broad, scope of substrates and reactions.[1] The second reason is the proprietary protection of established ligands.

If one considers that asymmetric hydrogenation with phosphine-containing catalysts begins with dipamp,[2] whose chirality derives from a phosphorus-based stereocenter, it seems paradoxical that the development of P-stereogenic ligands has been so slow.[3] A breakthrough came first with Imamoto's work on borane-protected phosphines,[4] which stimulated the recent development of powerful stereoselective synthetic methods. These are mainly based on diastereomerically pure oxazaphospholidine boranes[5] and on the enantioselective deprotonation of dimethylphosphine boranes[6a] or of racemic secondary phosphine boranes.[6b] An extremely promising *catalytic* approach to the synthesis of P-stereogenic phosphines is the asymmetric hydrophosphination of olefins.[7]

Jugé's method is excellently suitable for the introduction of *ortho*-substituted aryl groups onto a stereogenic phosphorus atom.[5] The diphosphines **1a**,[8a] **2a**,[8b,c] and **2b**,[8b,c] which have been developed in our and van Leeu-

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(1) Some classes of ligands. For binap, see: Akutagawa, S. *Appl. Catal., A:* **1995**, *128*, 171. Kumobayashi, H. *Recl. Trav. Chim. Pays-Bas* **1996**, *115*, 201. For Josiphos, see: Togni, A. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1475. For Duphos, see: Burk, M. J.; Gross, M. F.; Harper, T. G. P.; Kalberg, C. S.; Lee, J. R.; Martinez, J. P. *Pure Appl. Chem.* **1996**, *68*, 37.

(2) Seminal papers: (a) Knowles, W. S.; Sabacky, M. J.; Vineyard, B. D.; Weinkauff, D. J. *J. Am. Chem. Soc.* **1975**, *97*, 2567. (b) Vineyard, B. D.; Knowles, W. S.; Sabacky, M. J.; Bachmann, G. L.; Weinkauff, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 5946.

(3) For excellent reviews on the synthesis and applications of P-stereogenic ligands, see: (a) Pietrusiewicz, K. M.; Zablocka, M. *Chem. Rev.* **1994**, *94*, 1375. (b) Ohff, M.; Holz, J.; Quirmbach, M.; Börner, A. *Synthesis* **1998**, 1391.

(4) For a seminal paper, see: Imamoto, T.; Oshiki, T.; Onozawa, T.; Kusumoto, T.; Kazuhiko, S. *J. Am. Chem. Soc.* **1990**, *112*, 5244.

(5) Jugé, S.; Stéphan, M.; Laffitte, J. A.; Genet, J. P. *Tetrahedron Lett.* **1990**, *31*, 6357.

(6) (a) Muci, A. R.; Campos, K. R.; Evans, D. A. *J. Am. Chem. Soc.* **1995**, *117*, 9075. (b) Wolfe, B.; Livinghouse, T. *J. Am. Chem. Soc.* **1998**, *120*, 5116.

(7) (a) Kovacik, I.; Wicht, D. K.; Grewal, N. S.; Glueck, D. S.; Incarvito, C. D.; Guzei, I. A.; Rheingold, A. L. *Organometallics* **2000**, *19*, 950. (b) For the catalytic arylation of enantiomerically pure $P(BH_3)$-(CH_3)(Ph)H, see: Al-Masum, M.; Kumaraswamy, G.; Livinghouse, T. *J. Org. Chem.* **2000**, *65*, 4776.

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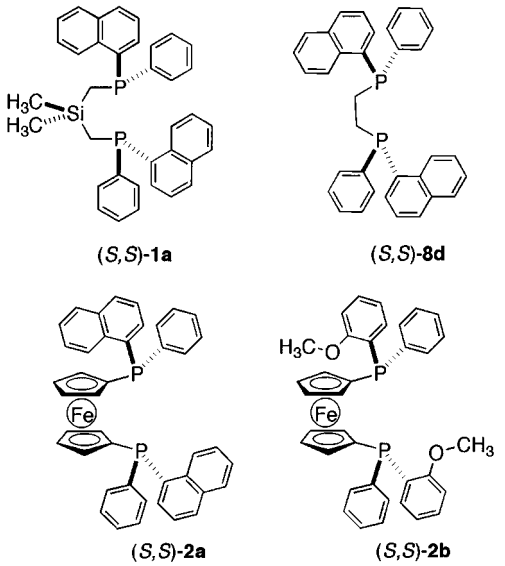
CHART 1



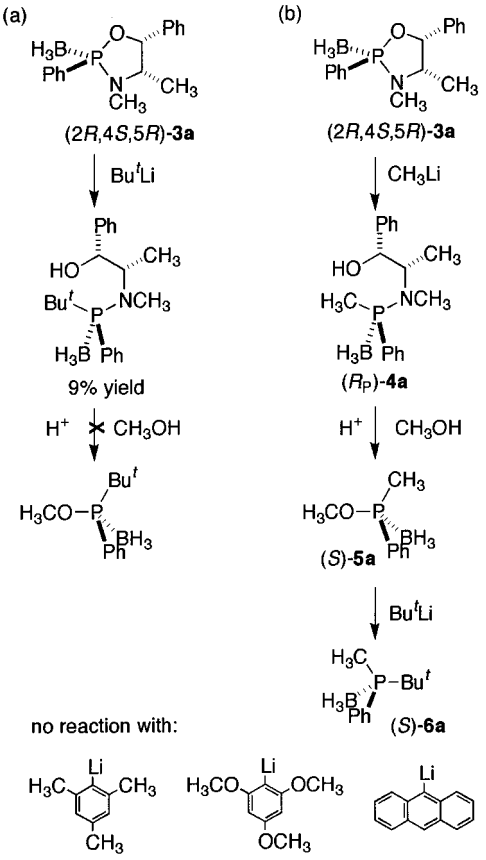
wen's laboratories with this method, are excellent ligands for the asymmetric hydrogenation of acetamido cinnamates (Chart 1). Unfortunately, the screening of different substrates suggests that these P-stereogenic ligands are specific for dehydroamino acids, whereas nonfunctionalized olefins and carbonyl compounds are hydrogenated with low enantioselectivity.[8a,b]

As the *ortho*-substituted aryls in ligands **1a**, **2a**, and **2b** assume different conformations both in solution and in the solid state,[8a,b] we speculated that the restricted scope of these ligands could be caused by the formation of rotamers. With this working hypothesis, we set out to develop strategies for the introduction of C_2-symmetric aryl substituents (or other highly symmetric, bulky groups) onto a stereogenic P atom. Some efforts in this direction have been undertaken independently by Brown and Jugé with the introduction of a ferrocenyl group at phosphorus.[9] Although this synthetic goal of preparing diphosphines containing very bulky P-substituents is not yet fully achieved, the results of the present investigation throw some light onto the relationship between the steric properties of the diphosphine and those of the P-substituents, as indicated by molecular modeling.

Results and Discussion

Synthesis of the Ligands. The first approach devised is the extension of Jugé's procedure to 2,6-disubstituted aryls (Scheme 1). In fact, in contrast to the *ortho*-substituted aryl groups (such as *o*-anisyl, 1-naphthyl, etc.), the oxazaphospholidine borane **3a** did not react with mesityllithium, 9-anthryllithium, or 2,4,6-trimethoxyphenyllithium. Only *tert*-butyllithium reacted, but in our

SCHEME 1



hands, the corresponding phosphinoamino alcohol **4** was produced in low yield (<15%) and was not isolated (Scheme 1b).[10] A modified approach was the introduction of the bulky substituent R in the third reaction step, that is, in the nucleophilic substitution at the P atom of phenylmethyl(methyl phosphinite) borane (*S*)-**5a** (Scheme 1b). Also in this case, only *tert*-butyllithium (3 equiv)[11] reacted with (*S*)-**5a** to give phenyl-*tert*-butylmethylphosphinoborane (*S*)-**6a** (66% yield). These attempts suggest that 2,6-disubstituted aryl groups are too bulky to react with either **3a** or **5a**, which restricts the application of the oxazaphospholidine methodology.

The reaction of (*S*)-**5a** with *t*-BuLi occurs with inversion of configuration at the P atom and gives (*S*)-**6**. This is confirmed by the (*S*,*S*) absolute configuration of the corresponding diphosphine (see below). The product was purified by chromatography and isolated with 92% ee. A further crystallization step gave the enantiomerically pure phosphine borane (*S*)-**6**. The enantiomeric excess of (*S*)-**6a** was determined by HPLC on a chiral column by comparison between the chromatograms of (*R*)-**6a** and (*S*)-**6a**.[12]

With (*S*)-**6** in our hands, we developed an alternative synthesis of 1,2-bis(*tert*-butylmethylphosphino)ethane,

(8) (a) Stoop, R. M.; Mezzetti, A.; Spindler, F. *Organometallics* **1998**, *17*, 668. (b) Maienza, F.; Wörle, M.; Steffanut, P.; Mezzetti, A.; Spindler, F. *Organometallics* **1999**, *18*, 1041. (c) Nettekoven, U.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Widhalm, M.; Spek, A. L.; Lutz, M. *J. Org. Chem.* **1999**, *64*, 3996. (d) Nettekoven, U.; Widhalm, M.; Kalchhauser, H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Lutz, M.; Spek, A. L. *J. Org. Chem.* **2001**, *66*, 759.

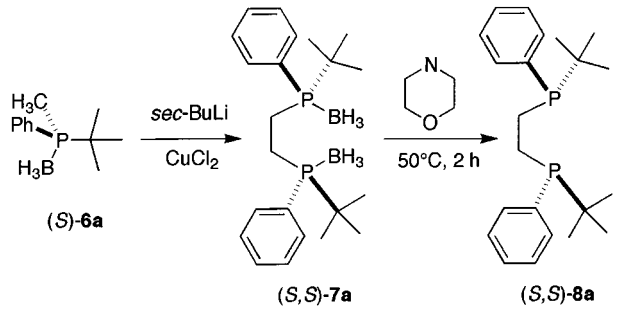
(9) (a) Brown, J. M.; Laing, J. C. P. *J. Organomet. Chem.* **1997**, *529*, 435. (b) Kaloun, E. B.; Merdès, R.; Genêt, J. P.; Uziel, J.; Jugé, S. *J. Organomet. Chem.* **1997**, *529*, 455.

(10) In contrast, other groups have managed to obtain good yields in the same reaction: (a) Moulin, D.; Darcel, C.; Jugé, S. *Tetrahedron: Asymmetry* **1999**, *10*, 4729. (b) Rippert, A. J.; Linden, A.; Hansen, H. J. *Helv. Chim. Acta* **2001**, *83*, 311.

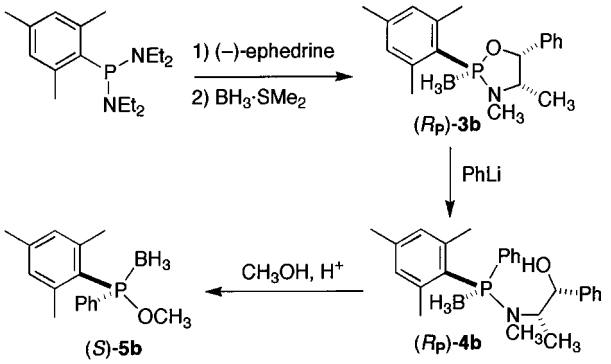
(11) One equivalent of RLi is consumed in the deprotonation of the methyl group.

(12) The enantiomeric phosphine borane (*R*)-**6a** was prepared with the same method starting from the oxazaphospholidine borane enantiomer (2*S*,4*R*,5*S*)-**3a**.

SCHEME 2



SCHEME 3

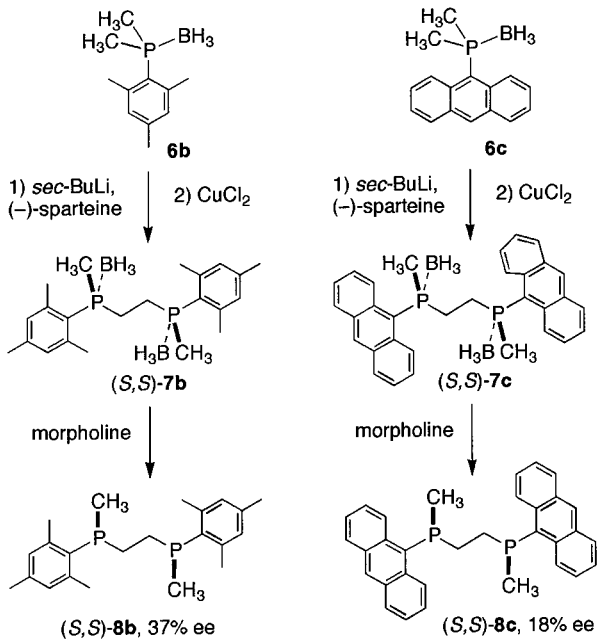


which Imamoto has prepared by fractional crystallization of diastereomeric menthyl esters.[4] The monodentate phosphine borane (*S*)-**6a** was deprotonated with *tert*-butyllithium at −78 °C in THF. The resulting $P(BH_3)(Ph)(Bu^t)(CH_2Li)$ was oxidatively coupled with Cu(II) to give the diphosphine borane (*S*,*S*)-**7a** (44% yield) (Scheme 2). The absolute configuration is attributed by assuming retention of configuration at the P atom. The free diphosphine (*S*,*S*)-**8a** was obtained from the phosphine borane (*S*,*S*)-**7a** by deprotection with morpholine at 50 °C and was purified by filtration on a short column of alumina under argon. The absolute configuration and enantiomeric purity (>98% ee) of (*S*,*S*)-**8a** were determined by comparison with the values reported by Imamoto for (*R*,*R*)-**8a**.[4]

The second approach was the introduction of a 2,6-disubstituted aryl group at the oxazaphospholidine stage. Diastereomerically pure (2*R*,4*S*,5*R*)-(−)-3,4-dimethyl-2-mesityl-5-phenyl-1,3,2-oxazaphospholidine-2-borane, (R_P)-**3b**, was obtained in 50% yield by refluxing bis(diethylamino)mesitylphosphine in toluene in the presence of (1*R*,2*S*)-(−)-ephedrine for 12 h, followed by protection with BH_3·SMe_2 (Scheme 3). The configuration at the P atom was assigned by analogy with the corresponding 2-phenyl-1,3,2-oxazaphospholidine borane (R_P)-**3a** (Scheme 1).[13] The ring-opening reaction with alkyllithium reagents gave low yields of **4b**, if at all, and was not synthetically useful. Indeed, mesityl oxazaphospholidine borane **3b** did not react with MeLi and reacted with PhLi, giving the corresponding amino alcohol (R_P)-**4b** in only 9% yield. The methanolysis of (R_P)-**4b** gave the phosphinite borane (*S*)-**5b** with 55% yield. Because of the low overall yields, the strategy was abandoned.

(13) Jugé, S.; Stephan, M.; Merdès, R.; Genêt, J. P.; Halut-desportes, S. *J. Chem. Soc., Chem. Commun.* **1993**, 531.

SCHEME 4



The next approach devised was based on Evans' sparteine-assisted enantioselective deprotonation of dimethylphosphine boranes $P(R)(Me)_2(BH_3)$.[6a] This method has been successfully applied for the synthesis of Ar(Me)-PCH_2CH_2P(Me)Ar (Ar = Ph, *o*-anisyl, *o*-tolyl, 1-naphthyl).[6a] By using the same method, Imamoto prepared (Me)(R)-PCH_2CH_2P(Me)(R) (R = Bu^t, CEt_3, *c*-C_5H_9).[14,15] We adapted this approach to our idea of using aryl substituents possessing C_2 symmetry (or higher). The mesityl group was introduced at the P atom by the reaction between $PCl(NEt_2)_2$ and mesityl magnesium bromide.[16] Pure $P(Mes)(NEt_2)_2$ (Mes = mesityl) was reacted, in sequence, with HCl, MeMgBr, and BH_3·SMe_2 to give the phosphine borane $P(Mes)(CH_3)_2(BH_3)$ (**6b**) in 80% overall yield. The 9-anthryl group was introduced at the P atom by reaction between $PCl(NEt_2)_2$ and 9-anthryllithium. Pure 9-anthryldichlorophosphine[17] was isolated and reacted sequentially with methyl magnesium bromide and BH_3·SMe_2 to give 9-anthryldimethylphosphine borane (**6c**) in good overall yield (70%).

The monophosphine borane **6b** was deprotonated with *s*-BuLi and oxidatively coupled with Cu(II) both in the presence of and without (−)-sparteine. The latter reaction, which gave access to the racemic diphosphines, yielded a mixture of the (*l*)- and (*u*)-diastereoisomers of 1,2-bis(mesitylmethylphosphino)ethane diborane, (*l*)-**7b** and (*u*)-**7b**, with 4:1 diastereoselectivity and 75% overall yield. In the case of the enantioselective deprotonation, **6b** was dissolved in THF and added to a mixture of (−)-sparteine and *s*-BuLi cooled at −78 °C (Scheme 4). The reaction mixture was warmed to −10 °C during 3 h to

(14) Imamoto, T.; Watanabe, J.; Wada, Y.; Masuda, H.; Yamada, H.; Tsuruta, H.; Matsukawa, S.; Yamaguchi, K. *J. Am. Chem. Soc.* **1998**, *120*, 1635.
(15) Imamoto, T. *Pure Appl. Chem.* **2001**, *73*, 373.
(16) van der Knaap, T. A.; Klebach, T. C.; Visser, F.; Bickelhaupt, F.; Ros, P.; Baerends, E. J.; Stam, C. H.; Konijn, M. *Tetrahedron* **1984**, *40*, 765.
(17) Wesemann, J.; Jones, P. G.; Schomburg, L.; Heuer, L.; Schmutzler, R. *Chem. Ber./Recl.* **1992**, *125*, 2187.

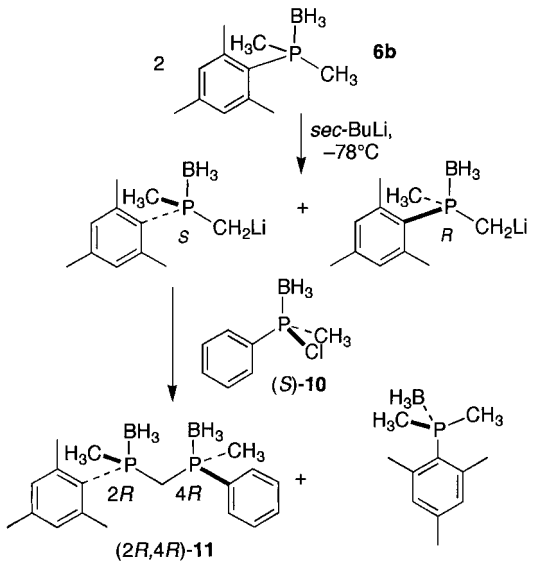
allow the deprotonation of **6b** and then cooled to −78 °C before adding $CuCl_2$ for the oxidative coupling step (Scheme 4). In this case, the reaction occurred with complete diastereoselectivity. Only (*l*)-**7b** was observed but with lower yield (62%). The enantiomeric excess was 37% (see below). Experiments directed at increasing the enantioselectivity were carried out at lower temperatures (−50 °C, −30 °C) and in different solvents (Et_2O, DME) but gave poor yields or no product at all.

When the coupling reaction of the 9-anthryl derivative **6c** was carried out without (−)-sparteine, a mixture of the diastereoisomers (*l*)-**7c** and (*u*)-**7c** was formed with 6:1 diastereoselectivity in 72% overall yield. In the case of the enantioselective deprotonation, the phosphine borane **6c** was added to a mixture of (−)-sparteine and *sec*-butyllithium cooled at −78 °C, and the mixture was stirred for 3 h at −78 °C before coupling with $CuCl_2$ (Scheme 4). Workup gave (*S*,*S*)-**7c** and (*R*,*S*)-**7c** in a 6:1 ratio and 70% total yield. Diastereomerically pure (*S*,*S*)-**7c** was obtained by crystallization from CH_2Cl_2/Et_2O with 39% yield and 18% ee.

The diphosphine boranes (*S*,*S*)-**7b** and (*S*,*S*)-**7c** were deprotected by stirring in morpholine solution at room temperature for 12 h. The diphosphines (*S*,*S*)-**8b** and (*S*,*S*)-**8c** were isolated after purification through a short column of alumina under argon. The enantiomeric excesses of (*S*,*S*)-**8b** and (*S*,*S*)-**8c** were determined on the corresponding phosphine oxides (*R*,*R*)-1,2-bis(*P*-oxomesitylmethylphosphino)ethane, (*R*,*R*)-**9b**, and (*R*,*R*)-1,2-bis(*P*-oxo-9-anthrylmethylphosphino)ethane, (*R*,*R*)-**9c**, which were prepared by oxidation of **8b** and **8c** with an excess of H_2O_2. In the presence of the chiral solvating agent (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol, (*R*,*R*)- and (*S*,*S*)-**9b** and (*R*,*R*)- and (*S*,*S*)-**9c** formed diastereomeric adducts with resolved ^{31}P NMR signals,[18] whose attribution was checked by comparison with the ^{31}P NMR spectra of racemic **9b** and **9c** recorded under the same conditions. The integration of these signals showed 37% ee in the case of the mesityl derivative (*R*,*R*)-**9b** and 18% ee in the case of (*R*,*R*)-**9c**. As the oxidation of trivalent phosphorus generally occurs with retention of configuration,[19] these values were taken as diagnostic of the enantiomeric excess of the diphosphines. The configurations *S*,*S* at the P atoms for the major enantiomer of the diphosphines were assigned by analogy to the other ligands prepared by enantioselective deprotonation with (−)-sparteine.[6a,14]

At this point, we tested the diastereoselective reaction between the racemic monodeprotonated phosphine borane and a suitable chiral synthon $P(BH_3)RR'X$. Preliminary experiments showed that the crucial point is the choice of X. Indeed, the phosphinite borane P(OMe)(Ph)(Me)(BH_3) (**5a**) did not react with P(R)(CH_3)(CH_2Li)(BH_3) (R = 9-anthryl or mesityl), even in the presence of an excess of the latter. Looking for more reactive synthons, we tried the chlorophosphine borane PCl(Ph)(Me)(BH_3) (**10**), which has been recently prepared by Jugé by acidolysis of **4a** with anhydrous HCl.[9b,10a,20] This procedure yields enantiomerically pure **10**, which we used as synthon for the asymmetrically substituted, methylene-bridged diphosphine (2*R*,4*R*)-2-mesityl-4-phenyl-2,4-diphosphapentane, (2*R*,4*R*)-**12** (Scheme 5). Ligand **12** is similar to Imamoto's MiniPHOS but has lower symmetry (C_1 instead of C_2).[21]

SCHEME 5



We prepared the chlorophosphine (*S*)-PCl(Ph)(CH_3)(BH_3) (**10**) described by Jugé[9b,10a,20] by reacting the phosphinoamino alcohol (R_P)-*N*-methyl[(1*S*,2*R*)-(2-hydroxy-1-methyl-2-phenyl)ethyl]aminomethylphenylphosphine borane, (R_P)-**4a**, with HCl (titrated Et_2O solution, 2.1 equiv vs **4a**) at room temperature. After 1 h, the ephedrine chlorohydrate was filtered off, and the formation of the chlorophosphine (*S*)-**10** was found to be quantitative by ^{31}P NMR spectroscopy. The 20 mM toluene/ether solution containing the chlorophosphine **10** was directly utilized for the reaction with the monodeprotonated, racemic P(Mes)(Me)(CH_2Li)(BH_3) (2 equiv). The latter was prepared by reaction of **6b** with *sec*-butyllithium in THF (at −78 °C),[22] and the resulting solution was added slowly to a solution of the chlorophosphine **10**, which was precooled at −78 °C (Scheme 5). The methylene-bridged diphosphine diborane (BH_3)(Me)(Mes)PCH_2P(BH_3)(Me)(Ph) (**11**) was isolated with a total yield of 66%. The (2*R*,4*R*)-diastereoisomer of **11** was formed predominantly and with >85% ee (see below). A minor diastereoisomer indicated as (*S*,*R*) was also formed in the reaction, as observed by ^{31}P NMR spectroscopy, which gave a ratio of 83:17 between the two diastereomers.[23]

The *absolute* stereochemistry at the P(4) atom of the major diastereoisomer was assumed to be *R*, considering that chlorophosphine boranes generally react with inversion of configuration at the P atom.[20] The *relative*

(18) Togni, A.; Pastor, S. D. *Tetrahedron Lett.* **1989**, *30*, 1071.
(19) Brown, J. M.; Carey, J. V.; Russell, M. J. H. *Tetrahedron* **1990**, *46*, 4877.
(20) Moulin, D. Ph.D. Thesis, Université de Cergy-Pontoise, 1999.

(21) (a) Yamanoi, Y.; Imamoto, T. *J. Org. Chem.* **1999**, *64*, 2988. (b) Gridnev, I. D.; Yamanoi, Y.; Higashi, N.; Tsuruta, H.; Yasutake, M.; Imamoto, T. *Adv. Synth. Catal.* **2001**, *343*, 118. (c) Gridnev, I. D.; Yasutake, M.; Higashi, N.; Imamoto, T. *J. Am. Chem. Soc.* **2001**, *123*, 5268.
(22) At temperatures higher than −78 °C, *sec*-butyllithium deprotonates also the *ortho*-methyl of the mesityl group. The lithiated mesityl methyl group reacts with the chlorophosphine **10** to give the diborane adduct of (2-(methylphenylphosphino)methyl-4,6-dimethylphenyl)dimethylphosphine. The latter was the main product when the deprotonation was carried out at 20 °C. Its formation was confirmed by NMR spectroscopy (^1H NMR, ^{13}C NMR, and ^{31}P,^1H NMR 2D correlation spectra).

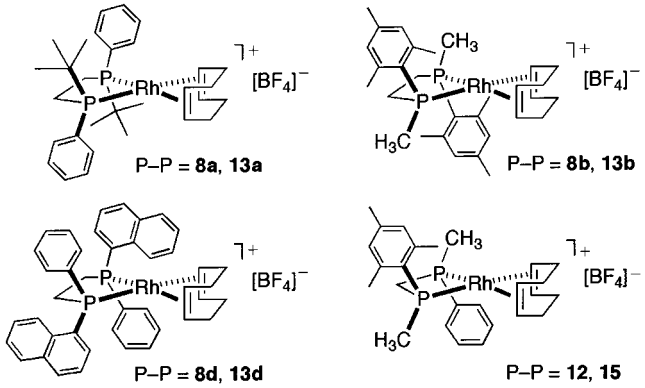
stereochemistry of the P atoms in the major diastereomer of **11** (and consequently in the free diphosphine (2*R*,4*R*)-(Ph)(CH_3)PCH_2P(Mes)(CH_3), (2*R*,4*R*)-**12**) was established by 2D NOESY spectroscopy on [Rh(COD)((2*R*,4*R*)-**12**)]$^+$, which confirmed that the methyl groups lie on opposite sides of the P−Rh−P plane (see below). Thus, the major diastereoisomer is regarded as (2*R*,4*R*)-**12**. Although no mechanistic study was carried out, a possible interpretation of the above results is that (*S*)-**10** reacts preferentially with (*S*)-P(BH_3)(Mes)(Me)(CH_2Li) to give (2*R*,4*R*)-**11** as the major product (83%).

To determine the enantiomeric excess of (*R*,*R*)-**11**, we prepared the opposite enantiomer (2*S*,4*S*)-**11** from the enantiomeric phosphinoamino alcohol (S_P)-**4a**. The chlorophosphine (*R*)-**10** was coupled with P(Mes)(CH_2Li)-(CH_3)(BH_3), as described above. The diastereomeric diphosphine boranes (2*S*,4*S*)-**11** and (2*R*,4*S*)-**11** were formed in a 5:1 ratio and were separated by flash chromatography. All four stereoisomers of **11** were separated by HPLC on a chiral column (Daicel Chiralcel OD-H). The peaks of the different diastereomers were attributed by comparison of the chromatograms of the products obtained from the enantiomeric phosphinoamino alcohols (R_P)-**4a** and (S_P)-**4a**. Thus, (*S*)-**10** gave (2*R*,4*R*)-**11** with 85.6% ee. The minor, pseudo-*meso* diastereomer (*S*,*R*)-**11** was formed with 81.8% ee. The enantiomeric chlorophosphine borane (*R*)-**10** gave (2*S*,4*S*)-**11** with 82.3% ee and (2*R*,4*S*)-**11** with 79.1% ee. As the ee values measured by Jugé for the phosphine boranes prepared from chiral chlorophosphines are in the range 80−90% ee,[20] (2*R*,4*R*)-**11** is formed with the same enantiomeric excess of the starting material (*S*)-**10**. Chromatographic purification gave diastereomerically pure (2*R*,4*R*)-**11**.

The deprotection of (2*R*,4*R*)-**11** with morpholine yielded the free diphosphine (2*R*,4*R*)-**12**. The enantiomer (2*S*,4*S*)-**12** was obtained from (2*S*,4*S*)-**11** by the same procedure. Diphosphines (2*R*,4*R*)-**12** and (2*S*,4*S*)-**12** were isolated as colorless oils after purification on a short column of alumina under argon to avoid oxidation. The ^{31}P NMR spectra of both enantiomers showed two doublets centered at δ −38 and δ −50 with $J_{P,P}$ = 144 Hz. The enantiomeric excess of **12** was determined by reprotection with $Me_2S{\cdot}BH_3$ and HPLC analysis on a chiral column. The enantiomeric excess of the resulting diphosphine borane (2*R*,4*R*)-**11** was the same as before de- and reprotection (86% ee). The same was observed for the enantiomeric product (2*S*,4*S*)-**11** (82% ee). This indicates that no epimerization occurs upon deprotection and that the P-configuration of the free diphosphines is stable in solution, as for Imamoto's ligands.[4,14,15] In contrast, the corresponding 1,2-ethanediyl-bridged ligands of the type (Ar)(Me)PCH_2CH_2P(Ar)(Me) (Ar = phenyl, *o*-anisyl, *o*-tolyl, 1-naphthyl) are configurationally unstable in solution.[6a]

(23) When a stoichiometric amount of (*rac*)-P(BH_3)(Me)(Mes)(CH_2-Li) (1 equiv vs **10**) was used, **11** was formed in less than 50% yield (on the basis of chlorophosphine **10**). With 2 equiv of (*rac*)-P(BH_3)(Me)-(Mes)(CH_2Li), the yield of **11** was 65%. The latter value did not improve when 3 equiv of (*rac*)-P(BH_3)(Me)(Mes)(CH_2Li) was used. The diastereomeric ratio (2*R*,4*R*)-**11**/(*S*,*R*)-**11** was roughly 5:1 in all experiments. The absolute configuration of the minor diastereoisomer of **11** is either (2*R*,4*S*) or (2*S*,4*R*). However, this is scarcely relevant from a practical viewpoint, as this isomer has pseudo-*meso* character, which makes it uninteresting, at least in principle, for asymmetric catalysis.

CHART 2



Rhodium Complexes. In previous work with P-stereogenic ligands, we have found that the isolated rhodium complexes give better enantioselectivity than the corresponding systems formed in situ.[8b] Also, the isolation of the complexes introduces a further purification step, which is particularly appropriate in the present case in view of the low (for **8b**) or moderate (for **12**) enantiopurity of some of the ligands. Thus, rhodium complexes of the type [Rh(COD)(P−P)]$^+$ (COD = 1,5-cyclooctadiene; P−P = diphosphine) were prepared with the P−P ligands (*S*,*S*)-**8a**, (*S*,*S*)-**8b**, (*S*,*S*)-**8d**, and (2*R*,4*R*)-**12**.

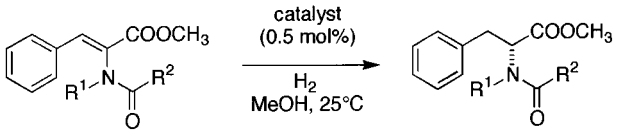
The reaction of [Rh($COD)_2$]BF_4 with (*S*,*S*)-**8a** (1 equiv) in THF gave analytically pure [Rh(COD)((*S*,*S*)-**8a**)]BF_4 (**13a**) (Chart 2). For the sake of comparison, we similarly prepared the rhodium derivative [Rh(COD)(**8d**)]BF_4 (**13d**), which contains the previously reported ligand (*S*,*S*)-1,2-bis(1-naphthylphenylphosphino)ethane[24] ((*S*,*S*)-**8d**). The ^{31}P NMR spectrum ($CDCl_3$, room temperature) of both complexes showed a regular doublet due to coupling to rhodium and, contrary to the cases of the analogues [Rh(COD)(P−P)]$^+$ (P−P = **1a** or **2a,b**),[8a−c] does not show any evidence of slow conformer interconversion.

The rhodium derivative [Rh(COD)((*S*,*S*)-**8b**)] (**13b**) containing the enantiomerically enriched ligand (*S*,*S*)-**8b** (37% ee) was prepared similarly as catalyst precursor for asymmetric hydrogenation. This was directed at assessing the performance of **8b** in catalysis and at deciding whether the preparation of the enantiomerically pure ligand should be investigated further. Complex **13b** was recrystallized from CH_2Cl_2/Et_2O to increase the enantiomeric excess, which, however, was not determined. After recrystallization, the specific rotation $[\alpha]_D^{20}$ of **13b** was −9.5 ($CHCl_3$, *c* = 0.15). The ^{31}P NMR spectrum consists of a doublet with $J_{Rh,P}$ = 145 Hz, which confirms that this highly symmetric 1,2-ethanediyl-bridged diphosphine does not form slowly interconverting conformers (at least in solution at room temperature).

The ligand (2*R*,4*R*)-**12** (86% ee) did not react with [Rh($COD)_2$]BF_4 or with [Rh($NBD)_2$]BF_4. In the case of Imamoto's MiniPHOS ligand Ph(Me)PCH_2P(Me)Ph (**14**), the reaction between [Rh($NBD)_2$]BF_4 and **14** afforded the bischelate complexes [Rh(**14**)$_2$]BF_4, even with the use of [Rh($NBD)_2$]BF_4 and the diphosphine in a 1:1 molar

(24) (a) Stoop, R. M.; Bauer, C.; Setz, P.; Worle, M.; Wong, T. Y. H.; Mezzetti, A. *Organometallics* **1999**, *18*, 5691. (b) For a nonstereoselective synthesis, see: Yoshikuni, T.; Bailar, J. C., Jr. *Inorg. Chem.* **1982**, *21*, 2129.

TABLE 1. Asymmetric Rh-Catalyzed Hydrogenation of Methyl *Z*-α-Acetamidocinnamates[a]



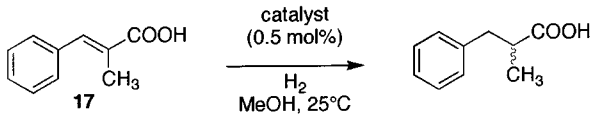
	ligand								product	
run	type	ee (%)	conf	substr	R^1	R^2	$p(H_2)$ (bar)	yield (%)	ee (%)	conf
1	**8a**	>98	(*S*,*S*)	**16a**	H	Me	1.1	>70	6.3	(*R*)
2	**8a**	>98	(*S*,*S*)	**16b**	Me	Me	1.1	>99	5.2	(*R*)
3	**8a**	>98	(*S*,*S*)	**16c**	Me	Ph	5.0	90	2.4	(*R*)
4	**8d**	>99	(*S*,*S*)	**16a**	H	Me	1.1	>99	98.6	(*S*)
5	**8d**	>99	(*S*,*S*)	**16b**	Me	Me	1.1	37	18.3	(*S*)
6	**8d**	>99	(*S*,*S*)	**16c**	Me	Ph	6	33	26.9	(*S*)
7	**8b**	37	(*S*,*S*)	**16a**	H	Me	1.1	37	racemic	
8[b]	**8b**	37	(*S*,*S*)	**16b**	Me	Me	5.0	>99	racemic	
9	**12**	86	(2*R*,4*R*)	**16a**	H	Me	1.0	>99	racemic	

[a] Other reaction conditions: 18 h reaction time, unless otherwise stated. [b] The reaction time was 65 h.

ratio.[21a] In the case of C_1-MiniPHOS (2*R*,4*R*)-**12**, no reaction occurred even when 2 equiv of diphosphine versus $Rh[(NBD)_2]BF_4$ was used. Thus, we prepared [Rh(COD)((2*R*,4*R*)-**12**)]PF_6 (**15**) by reaction of the dinuclear rhodium complex $[RhCl(COD)]_2$ with (2*R*,4*R*)-**12** in THF in the presence of NH_4PF_6. The ^{31}P NMR spectrum consists of two doublets of doublets centered at δ −10.6 and δ −22.0, with $J_{P,P} = 80$ Hz and $J_{P,Rh} = 95$ Hz, respectively. A 2D NOESY spectrum (see Supporting Information, Figure S1) did not show any cross peak for the methyl groups bonded to the P atoms (δ 1.81 and δ 2.03), confirming that they are positioned on opposite sides with respect to the P−Rh−P plane. Molecular modeling (Cerius 2) shows that, in the (*S*,*R*)-diastereoisomer, the two methyl groups are as close as 2.73 Å (Figure S2) and should therefore give rise to significant transfer of magnetization in the 2D NOESY spectrum. Additionally, only one conformer was observed in solution at room temperature, confirming that the combination of C_2-symmetric substituents at the P atoms with a rigid backbone reduces the conformational freedom of the ligand in the rhodium complexes $[Rh(diolefin)(P-P)]^+$.

Rh-Catalyzed Asymmetric Hydrogenation. Complexes **13a**, **13b**, **13d**, and **15** were tested in the rhodium(I)-catalyzed hydrogenation of functionalized olefins. The results of the asymmetric hydrogenation of α-acetamidocinnamic acid derivatives are summarized in Table 1. Complex **13a** hydrogenated methyl (*Z*)-α-acetamidocinnamate (**16a**) to (*R*)-*N*-acetylphenylalanine methyl ester (**16a**H_2) with 6.3% ee at 20 °C and 1 bar H_2 (run 1). Also, the *N*-methylated analogues methyl (*Z*)-*N*-methyl-α-acetamidocinnamate (**16b**) and methyl (*Z*)-*N*-methyl-α-benzamidocinnamate (**16c**) were hydrogenated with low enantioselectivity (runs 2, 3), whereas the analogous complexes containing **1a** and **2a,b** have been found to be excellent catalysts for this reaction.[8a,b] Complex **13d**, which contains the dipamp-analogue **8d**, hydrogenated **16a** with excellent enantioselectivity (98.6%, run 4), which exceeds the 97.5% ee obtained with the dipamp rhodium catalyst.[2] Bailar and Yoshikuni have reported that [Rh(COD)(**8d**)]$^+$ hydrogenates α-acetamido acrylic acid with 76% ee.[24b] Complex **13d** is much less efficient in the hydrogenation of the *N*-methylated substrates **16b** and **16c** (runs 5 and 6).

TABLE 2. Asymmetric Rh-Catalyzed Hydrogenation of *E*-2-Methylcinnamic Acid[a]



	ligand					
run	type	ee (%)	$p(H_2)$ (bar)	time (h)	yield (%)	ee (%)
1[b]	**8a**	>98	5	65	>95	3
2	**8d**	>99	6	65	>95	34
3[b]	**12**	>99	5	17	53	racemic

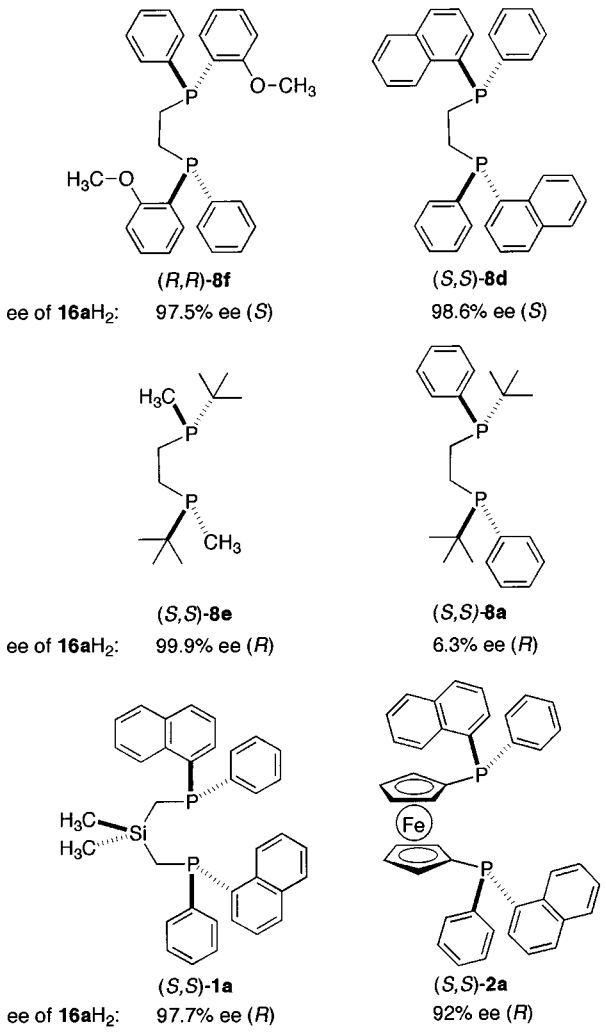
[a] Other reaction conditions: NEt_3 (2 mL) was added to the reaction solution. The absolute configuration of the product was not determined. [b] A black precipitate, presumably rhodium metal, was observed at the end of the reaction.

We also tested complex **13b**, which contains enantiomerically enriched (*S*,*S*)-**8b** (37% ee). Two experiments were carried out in the asymmetric hydrogenation of methyl (*Z*)-α-acetamidocinnamate (**16a**) (run 7) and methyl (*Z*)-α-*N*-methyl acetamidocinnamate (**16b**) (run 8). Both these substrates gave the racemic products (0% ee). This suggests that, independently from the low enantiomeric purity of the ligand (37% ee), the chirality transfer from ligand (*S*,*S*)-**8b** is inefficient. Therefore, no further experiments were carried out with complex **13b**, and no attempts to increase its enantiomeric purity were undertaken. Finally, also ligand **12** gave disappointing results. Methyl (*Z*)-α-acetamidocinnamate (**16a**) was converted quantitatively (>99% yield) to the racemic *N*-acetylphenylalanine methyl ester (run 9).

To better define the scope of the ligands, we also tested (*E*)-2-methylcinnamic acid (**17**) as substrate. Complex **13d** hydrogenated **17** with low enantioselectivity (34% ee, Table 2, run 2), and **13a** and **15** gave racemic (*E*)-2-methyldihydrocinnamic acid (runs 1 and 3). With the latter complexes, a black precipitate, presumably rhodium metal, was observed at the end of the catalytic reaction. This fact suggests that ligands **8a** and **12** coordinate weakly to rhodium in at least one of the rhodium complexes involved in the catalytic cycle, as will be discussed below.

Chart 3 summarizes the effect of changing the substituents at *stereogenic phosphorus* in the ligands R(R′)-

CHART 3



$PCH_2CH_2P(R')R$ on the enantioselectivity of the hydrogenation of **16a**. The catalytic results show that the ideal combinations for the two terminal substituents at phosphorus are either two aryl groups, such as in **8f**,[2] **8d**, **1a**,[8a] and **2a**,[8b] or two alkyl groups, such as in **8e**.[14,21b] In contrast, the combination of an aryl with an alkyl group in (Ar)(R)P-groups is inefficient, as indicated by the low enantioselectivity obtained with **8a**. Similar considerations hold for the methylene-bridged diphosphines **12** and **14**. In fact, $Me(Ph)PCH_2P(Me)Ph$, the only ligand of the MiniPHOS series featuring an aryl and an alkyl group, hydrogenated (*E*)-2-acetamidoacrylic acid with only 26% ee.[21a] In the following sections, we suggest two possible explanations for this observation.

Quadrant Rule and Molecular Modeling. We carried out molecular modeling (MM) calculations (Cerius^2)[25] to find out the preferred conformation of the P-substituents of (*S*,*S*)-**8a** in the rhodium complex **13a**. The aim was to correlate the absolute configuration of the phenylalanine derivative **16a**H_2 with the ligand conformation by means of the "quadrant rule", as proposed by Knowles[26]

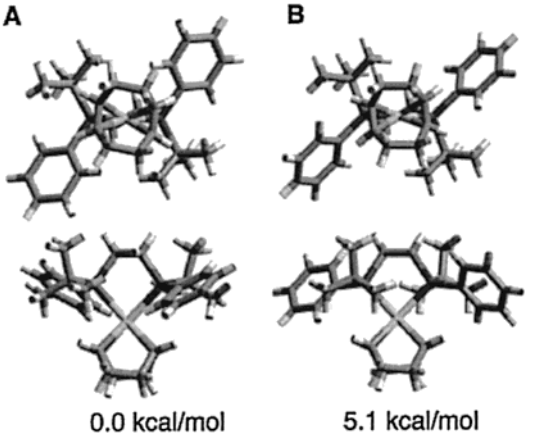


FIGURE 1. Energy-minimized (Cerius^2) conformations of $[Rh(COD)(\mathbf{8a})]^+$ (**13a**) with relative energies.

and extended by Imamoto.[27] The quadrant rule predicts the (*S*) configuration for **16a**H_2 when bulky substituents are present in the lower left and upper right quadrants (as seen from the side of the olefin).[26]

It is of interest to note that Knowles' formulation, which was based on structural data of the dipamp (**8f**) complex $[Rh(COD)(\mathbf{8f})]^+$,[26] implies that the role of the "small" substituent is played by the larger aryl group, which occupies an equatorial position with a face-on conformation. The "bulky" substituents are the smaller phenyl groups, which are forced in an axial, edge-on conformation. The steric hindrance of the phenyl groups is caused by their edge-on conformation with respect to the incoming olefin. Accordingly, ligand (*R*,*R*)-**8f** gives (*S*)-**16a**H_2 (Chart 3).[2] This holds when *two aryl substituents* are present at the stereogenic P atom. In the case of diphosphines bearing *two (highly symmetrical) alkyl groups*, Imamoto has shown that the "absolute bulkiness" of the alkyl group determines the absolute configuration of **16**H_2 in agreement with the quadrant rule.[27] Thus, ligand (*S*,*S*)-**8e** gives (*R*)-**16**H_2 (Chart 3).[27]

In this context, the intermediate case, in which *an aryl group is combined with a bulky alkyl group*, is particularly interesting. The MM calculations on **13d** indicate that two conformations of the phenyl rings are possible (Figure 1). In the more stable conformation **A**, the phenyl groups are face-on with respect to the sp^2 plane of the coordinated C═C bond, and the equatorial and axial positions are not clearly defined. The conformation **B** is 5 kcal/mol higher in energy and features clearly distinguishable axial and equatorial positions, with edge-on phenyl groups in the latter. van der Waals contacts in **B** (ΔE = 6.3 kcal mol^{-1}) account for the large energy difference between **A** and **B**. In the latter, the phenyl groups play the role of the bulky substituent, as they are edge-on. The conformational change from **B** to **A** involves the rotation of the phenyl groups from the edge-on to the face-on conformation. This change reduces the "relative steric bulk" of Ph, as compared to Bu^t. Consequently, the equatorial phenyl groups move away from the equatorial positions in **B** to give rise to the flattened conformation of **A**, in which the equatorial and axial positions are not clearly defined.

(25) Cerius^2 uses the Universal Force Field (UFF): Rappé, A. K.; Casewit, C. J.; Colwell, K. S.; Goddard, W. A., III; Skiff, W. M. *J. Am. Chem. Soc.* **1992**, *114*, 10024. Rappé, A. K.; Colwell, K. S.; Casewit, C. J. *Inorg. Chem.* **1993**, *32*, 3438.

(26) Knowles, W. S. *Acc. Chem. Res.* **1983**, *16*, 106.

(27) Gridnev, I. D.; Higashi, N.; Asakura, K.; Imamoto, T. *J. Am. Chem. Soc.* **2000**, *122*, 7183.

The conformational difference between **A** and **B** is small but distinct (note the relative positions of the *ipso*-C atoms of the Ph and Bu^t groups). The (unfortunate) overall effect is that, in the most stable conformer **A**, the Ph and Bu^t groups have nearly the same (apparent) steric bulk, as indicated by the flattening of the half-chair conformation[28] and as reflected by the very low enantioselectivity (6.3% ee) observed in the hydrogenation of **16a** by complex **13a**. Application of the quadrant rule suggests that *tert*-butyl is slightly more bulky than phenyl, as (*R*)-**16a**H_2 is formed with ligand (*S*,*S*)-**8a**. We conclude that the combination of *one alkyl and one aryl group* destroys the interplay of the two aryl groups and allows for the detrimental conformational flexibility, as discussed for ligand **8a**. Clearly, such effects are difficult to predict on paper, and MM calculations can be very helpful. Interestingly, van Koten[29] has recently reported that a P-stereogenic PCP pincer ligand containing the P(Bu^t)Ph group gives lower enantioselectivity in the palladium-catalyzed aldol condensation of 2-isocyanoacetate and benzaldehyde than the related C-stereogenic analogue developed by Venanzi and Zhang.[30]

The quadrant rule is an extraordinarily successful rule-of-thumb to predict the absolute configuration of the hydrogenation product **16a**H_2 with a number of different ligands including, besides dipamp, the already mentioned **1**, **2a**, and **2b**. Therefore, we were surprised to find that ligand **8d** is an exception. In fact, (*S*)-**16a**H_2 is formed with [Rh(COD)((*S*,*S*)-**8d**)]$^+$, instead of the expected (*R*) enantiomer (Table 1, run 4). Also, the *N*-methylated substrates **16b** and **16c** give the (*S*) products (runs 5 and 6). This behavior is exceptional, as the related ligands with a similar stereogenic environment, such as **1a**[8a] and **2a**[8b,c] (besides dipamp **8f** itself),[2] give (*R*)-**16a**H_2.[31] We conclude that, albeit extremely useful, the quadrant rule should be applied with caution, as the steric interplay in the [Rh(diolefin)(P−P)]$^+$ complexes is complicated, and it is even more so in the intermediates of the catalytic cycle.

Stability of the Catalytic System. With ligands **8a** and **12**, a black precipitate of rhodium metal is observed after the reaction time. The occurrence of a parallel heterogeneous reaction is an alternative explanation of the low enantioselectivity observed with ligands **8a**, **8b**, and **12**. As the instability of the rhodium complexes containing these ligands is not self-evident, we suggest a possible explanation thereof. This is based on Imamoto's observation that increasing the basicity of the diphosphine ligands substantially favors the oxidative addition of dihydrogen, as compared to bis(aryl)diphosphines.[27] With ligands of the type RR′P−PRR′ (R = alkyl group), this causes the change from the unsaturated to the dihydride mechanism. It is possible that the dialkyl-aryl ligands Ar(R)P−P(R)Ar are basic enough to switch on the "dihydride mechanism" but are *not basic enough* to afford a substantial stabilization of the resulting dihydride complex, which decomposes during the catalytic reaction. We speculate that steric effects (including chelate ring size) enhance this effect. In fact, ligand **8a** bears two bulky substituents at phosphorus, one of which is an alkyl group (*tert*-butyl). In **8b**, the mesityl group is also extremely bulky. In ligand **12**, the strained four-membered ring labilizes the Rh−P bond, introducing a further element of instability.

Conclusion

The stereoselective introduction of 2,6-disubstituted aryl groups at stereogenic phosphorus is still a challenge. Amenable synthetic protocols led to some new methylaryl-substituted diphosphines, which, however, turned out to be ineffective in the rhodium-catalyzed hydrogenation of olefins. The present study suggests that this is a more general problem, which is possibly related to the *combination of an alkyl and an aryl substituent* rather than to the nature of the aryl substituent alone. Indeed, whereas (both new and well-established) bis(aryl)- and bis(alkyl)-substituted ligands are highly effective in the rhodium-catalyzed hydrogenation of acetamidocinnamic esters, all the mixed arylalkyl derivatives R(Ar)PCH_2-CH_2P(Ar)R tested are not. Both steric (R = Bu^t) and electronic reasons (R = Me, Bu^t) account for the low performance of R(Ar)PCH_2CH_2P(Ar)R. Still, such ligands should be tested in catalytic reactions other than the rhodium-catalyzed hydrogenation of olefins. A posteriori, some of the results can be rationalized by simple molecular modeling calculations, suggesting that the sensible application of molecular modeling should be used as a tool guiding synthetic work.

Experimental Section

General Comments. Reactions with air- or moisture-sensitive materials were carried out under an argon atmosphere using Schlenk techniques. Solvents were purified by standard procedures. P(Mes)$(NEt_2)_2$,[16] 9-anthryldichlorophosphine,[17] (2*R*,4*S*,5*R*)-3,4-dimethyl-2,5-diphenyl-1,3,2-oxazaphospholidine-2-borane ((2*R*,4*S*,5*R*)-**3a**) (and its enantiomer (2*S*,-4*R*,5*S*)-**3a**),[5,9b] (R_P)-*N*-methyl[(1*S*,2*R*)-(2-hydroxy-1-methyl-2-phenyl)ethyl]aminomethylphenylphosphine borane ((R_P)-**4a**) (and its enantiomeric form (S_P)-**4a**),[5,9b] (*S*)-phenylmethyl-(methyl phosphinite) borane ((*S*)-**5a**),[5] and (*S*,*S*)-1,2-bis(1-naphthylphenylphosphino)ethane (**8d**)[24a] were prepared according to literature procedures. The ^{1}H, ^{31}P, and ^{11}B NMR, mass spectra, HPLC, GC, melting points, specific rotations, and elemental analyses were measured as described before.[8b]

(*S*)-(−)-*tert*-Butylphenylmethylphosphinoborane, (*S*)-6a. A 1.7 M hexane solution of *t*-BuLi (48.2 mL, 0.082 mol, 3 equiv vs **5a**) was added slowly to a solution of (*S*)-**5a** (4.59 g, 0.027 mol) in THF (60 mL) cooled at −78 °C, and the resulting solution was then allowed to reach room temperature overnight. The reaction was quenched with H_2O (60 mL), THF was evaporated, and the product was extracted with CH_2Cl_2 and dried with $MgSO_4$. Evaporation of the solvent and flash chromatography (silica gel, hexane/ethyl acetate 95:5, R_f 0.32) gave (*S*)-**6a** as a white solid (46 g, 66%, 0.018 mol). HPLC (OD, hexane/2-propanol 99:1): R_t (*S*)-**6a** = 10.5 min, R_t (*R*)-**6a** = 11.3 min (92% ee). The enantiomerically pure product (only (*S*)-**6a** was detected) was obtained by recrystallization from hot hexane. $[\alpha]_D^{20} = -4.6$ (*c* 1, $CHCl_3$).^{31}P NMR ($CDCl_3$): δ 9.7 (br q, 1P). ^{1}H NMR ($CDCl_3$): δ 7.75−7.46 (m, 5H, 1Ph),

(28) The negative effects of the flattening of the chelate ring on enantioselectivity have been thoroughly discussed by Seebach for a number of chiral diphosphines: Seebach, D.; Devaquet, E.; Ernst, A.; Hayakawa, M.; Kühnle, F. N. M.; Schweizer, W. B.; Weber, B. *Helv. Chim. Acta* **1995**, *78*, 1636.

(29) Williams, B. S.; Dani, P.; Lutz, M.; Spek, A. L.; van Koten, G. *Helv. Chim. Acta* **2001**, *84*, 3519.

(30) (a) Gorla, F.; Togni, A.; Venanzi, L. M.; Albinati, A.; Lianza, F. *Organometallics* **1994**, *13*, 1607. (b) Longmire, J. M.; Zhang, X.; Shang, M. *Organometallics* **1998**, *17*, 4374.

(31) Consistently with our observation, (−)-[Rh(COD)(**8d**)]Cl (in which ligand **8d** has the *S*,*S* configuration, according to our attribution) hydrogenates α-acetamidoacrylic acid to *N*-acetyl-(*S*)-alanine.[24b]

1.55 (d, 3H, $J_{P,H}$ = 8.9 Hz, 1CH_3), 0.86 (s, 9H, 3CH_3), 1.3−0.8 (br, 3H, BH_3). MS *m*/*z* (FAB$^+$): 180 (M^+ − BH_3, 9), 151 (M^+ − BH_3 − 2CH_3, 80), 124 (M^+ − BH_3 − 4CH_3 + 3H, 63). Anal. Calcd for $C_{11}H_{20}BP\cdot0.25C_6H_{14}$: C, 69.64; H, 10.98. Found: C, 70.05; H, 10.02.

(*R*)-(+)-*tert*-Butylphenylmethylphosphinoborane, (*R*)-6a. (*R*)-**6a** was prepared and purified as described for (*S*)-**6a** starting from (*R*)-P(OMe)(Ph)(Me)(BH_3). Same spectroscopic properties as (*S*)-**6a**, 91% ee (by HPLC, see above).

(*S*,*S*)-(−)-1,2-Bis(*tert*-butylphenylphosphino)ethane Diborane, (*S*,*S*)-7a. A 1.2 M hexane solution of *s*-BuLi (5.5 mL, 6.63 mmol) was added slowly to a solution of (*S*)-P(Ph)(Bu^t)(Me)(BH_3), (*S*)-**6a**, (1.175 g, 6.03 mmol) in THF (50 mL) cooled at −78 °C. The reaction solution was stirred for 3 h at −78 °C. A suspension of $CuCl_2$ (2.43 g, 18.1 mmol) in THF (43 mL) was added slowly by cannula, and the resulting solution was allowed to reach room temperature overnight. The reaction was quenched with 1 M HCl (50 mL) and diluted with ethyl acetate. The organic layer was washed with 37% NH_3 (15 mL), brine (15 mL), and water (2 × 15 mL) and dried with $MgSO_4$, and the solvent was evaporated. Crystallization from hot hexane gave (*S*,*S*)-**7a** as a white solid (510 mg, 44%). $[\alpha]_D^{20}$ = −37 (*c* 1, $CHCl_3$).[4] ^{31}P NMR ($CDCl_3$): δ 19.4 (br q, 2P). ^{1}H NMR ($CDCl_3$): δ 7.70−7.42 (m, 10 H, 2Ph), 1.88−1.56 (m, 4H, 2CH_2), 0.83 (s, 18H, 6CH_3), 1.28−0.67 (br, 6 H, 2BH_3). MS *m*/*z* (FAB$^+$): 358 (M^+ − 2BH_3, 33), 329 (M^+ − C$(CH_3)_3$, 100). Anal. Calcd for $C_{22}H_{38}B_2P_2$: C, 68.44; H, 9.92. Found: C, 68.62; H, 9.53.

(*S*,*S*)-(−)-1,2-Bis(*tert*-butylphenylphosphino)ethane, (*S*,*S*)-8a. (*S*,*S*)-1,2-Bis(*tert*-butylphenylphosphino)ethane diborane, (*S*,*S*)-**7a**, (300 mg, 0.78 mmol) was dissolved in morpholine (5 mL). The solution was stirred for 2 h at 50 °C and then evaporated to dryness at room temperature. Chromatography (alumina, toluene) under argon gave pure (*S*,*S*)-**8a** (260 mg, 93%). The absolute configuration and enantiomeric purity of (*S*,*S*)-**8a** ($[\alpha]_D^{20}$= −78, C_6H_6, *c* 0.9, >98% ee) were determined by comparison with the values reported by Imamoto for (*R*,*R*)-**8a** ($[\alpha]_D^{20}$ = +78.7, *c* 0.9, C_6D_6).[4] ^{31}P NMR ($CDCl_3$): δ −18.6 (s, 2P). ^{1}H NMR ($CDCl_3$): δ 7.50−7.32 (m, 10H, 2Ph), 2.8 (m, 4H, 2CH_2), 0.82 (s, 18H, 6CH_3). MS *m*/*z* (FAB$^+$): 358 (M^+, 47), 329 (M^+ − C$(CH_3)_3$, 100). Anal. Calcd for $C_{22}H_{38}B_2P_2$: C, 73.73; H, 9.00. Found: C, 73.62; H, 9.17.

(2*R*,4*S*,5*R*)-(+)-3,4-Dimethyl-2-mesityl-5-phenyl-1,3,2-oxazaphospholidine-2-borane, (R_P)-3b. (1*R*,2*S*)-(−)-Ephedrine (6.41 g, 0.039 mol) was added to a solution of P(Mes)$(NEt_2)_2$ (11.445 g, 0.039 mol) in toluene (220 mL). The solution was refluxed for 15 h and then cooled to room temperature. $BH_3\cdot SMe_2$ (11.1 mL, 8.88 g, 0.117 mol) was added under stirring. After 3 h, the solvent was evaporated, and the resulting thick oil was purified by flash chromatography (silica gel, hexane/ethyl acetate, R_f 0.4). Pure (R_P)-**3b** (one single diastereoisomer) was isolated as a white crystalline solid (5.359 g, 42%, 0.016 mol). $[\alpha]_D^{20}$ = +5.7 (*c* 1, $CHCl_3$). Mp 102 °C. ^{31}P NMR ($CDCl_3$): δ 138.3 (s, 1P). ^{1}H NMR ($CDCl_3$): δ 7.42−7.27 (m, 5H, Ph*H*), 6.85−6.84 (m, 2H, Mes*H*), 5.16 (dd, 1H, $^3J_{H,H'}$ = 5.8 Hz, $^3J_{P,H}$ = 3.8 Hz, OC*H*Ph), 3.64 (m, 1H, NC*H*Me), 2.87 (d, 3H, $^3J_{P,H}$ = 10.5 Hz, NCH_3), 2.54 (s, 6H, 2CH_3), 2.24 (s, 3H, CH_3), 0.85 (d, 3H, $^3J_{H,H'}$ = 6.7 Hz, CH_3), 1.7−0.2 (m, 3H, BH_3). MS *m*/*z* (FAB$^+$): 326 (M^+, 66), 313 (M^+− BH_3, 100).

(R_P)-(+)-*N*-Methyl[(1*S*,2*R*)-(2-hydroxy-1-methyl-2-phenyl)ethyl]aminomesitylphenylphosphine Borane, (R_P)-4b. A hexane solution of PhLi (16.9 mL, 0.02 mol, 1.18 M, 1.6 equiv vs **3b**) was added slowly to a THF solution (18 mL) of (R_P)-**3b** (5.083 g, 0.0156 mol) cooled at −78 °C. After stirring for 30 min at −78 °C, the solution was allowed to reach room temperature overnight. The reaction was quenched with H_2O (20 mL), and the THF was removed under vacuum. The crude product was extracted with CH_2Cl_2 and dried over $MgSO_4$. Evaporation of the solvent and flash chromatography (silica gel, toluene, R_f 0.19) gave (R_P)-**4b** as a single diastereoisomer (0.57 g, 91%). $[\alpha]_D^{20}$ = +17.2 (*c* 1, CH_2Cl_2). Mp 105 °C. ^{31}P NMR ($CDCl_3$): δ 65.8 (br q, 1P). ^{1}H NMR ($CDCl_3$): δ 7.47−7.16 (m, 12H, Ar*H*), 4.68 (d, 1H, $^3J_{H,H'}$ = 7.0, C*H*(Ph)OH), 4.06 (m, 1H, NC*H*Me), 3.46 (d, 3H, $^3J_{P,H}$ = 6.2, NCH_3), 2.25 (s, 6H, 2CH_3), 2.15 (s, 3H, CH_3), 2.01 (br s, 1H, O*H*), 1.82 (d, 3H, $^3J_{H,H}$ = 9.1, NC(CH_3)H), 1.69 (d, 3H, $^3J_{P,H}$ = 6.0, PCH_3), 1.8−0.5 (m, 3H, BH_3). MS *m*/*z* (FAB$^+$): 404 (M^+ − H, 100), 392 (M^+ − BH_3, 31), 284 (M^+ − H − Mes, 42), 227 (M^+ − BH_3 − ephedrine, 39).

(*S*)-(−)-Mesitylphenyl(methyl phosphinite) Borane, (*S*)-5b. Concentrated H_2SO_4 (0.12 mL, 97%) was added to a solution of the aminophosphine borane (R_P)-**4b** (0.855 g, 2.1 mmol) in MeOH (20 mL) at room temperature. The reaction solution was stirred for 15 h. After evaporation of the solvent, flash chromatography (silica gel, hexane/ethyl acetate 95:5, R_f 0.18) gave pure (*S*)-**5b** (0.286 g, 55%). $[\alpha]_D^{20}$ = −23 (*c* 1, $CHCl_3$). ^{31}P NMR ($CDCl_3$): δ 112.8 (br, 1P). ^{1}H NMR ($CDCl_3$): δ 7.86−7.31 (m, 7H, Ar*H*), 3.63 (d, 3H, $J_{P,H}$ = 12.2 Hz, POCH_3), 2.21 (s, 6H, 2CH_3), 2.12 (s, 3H, CH_3), 1.82 (d, 3H, $^3J_{P,H}$ = 9.1 Hz, PCH_3), 1.3−0.6 (m, 3H, BH_3). MS *m*/*z* (FAB$^+$): 258 (M^+ − BH_3, 84), 243 (M^+ − BH_3 − CH_3, 41), 196 (M^+ − Ph, 100).

Mesityldimethylphosphine Borane, 6b. A HCl solution (1 M in Et_2O, 206 mL, 0.206 mol) was added to P(Mes)$(NEt_2)_2$ in THF (200 mL). The resulting solution was stirred for 1 h, and the white precipitate was filtered off. After cooling to −78 °C, a 3 M Et_2O solution of MeMgCl (70 mL, 0.21 mol) was added slowly. The solution was stirred for 3 h, during which it reached room temperature. The magnesium chloride was filtered off, and $BH_3\cdot SMe_2$ (29.3 mL, 23.47 g, 0.309 mol) was slowly added. The solution was stirred for 3 h, and then the solvent was evaporated. Chromatography (silica gel, toluene) gave **6b** as a colorless oil (15 g, 77%, 0.77 mol).^{31}P NMR ($CDCl_3$): δ 0.1 (br q, 1P). ^{1}H NMR ($CDCl_3$): δ 6.89 (m, 2H, Ar*H*), 2.59 (s, 6H, 2 CH_3), 2.37 (s, 3H, CH_3), 1.74 (d, 6H, 2CH_3, $J_{P,H}$ = 9.8 Hz), 1.64−1.04 (br, 3H, BH_3). MS *m*/*z* (FAB$^+$): 180 (M^+ − BH_3, 100), 165 (M^+ − BH_3 − CH_3, 33), 45 (M^+ − BH_3 − CH_3 − Mes, 72).

(*S*,*S*)-(+)-1,2-Bis(mesitylmethylphosphino)ethane Diborane, (*S*,*S*)-7b. A 1.3 M hexane solution of *s*-BuLi (3.5 mL, 4.52 mmol) was added slowly to a solution of (−)-sparteine (1.04 mL, 1.06 g, 4.52 mmol) in THF (15 mL) cooled at −78 °C. After stirring for 15 min, a solution of P(Mes)$(Me)_2(BH_3)$ (0.797 g, 4.106 mmol) in THF (20 mL) cooled at −78 °C was added slowly thereto. The resulting solution was warmed to −10 °C during 3 h and then cooled to −78 °C. A suspension of $CuCl_2$ (1.657 g, 12.319 mmol) in THF (20 mL) was added slowly by cannula, and the resulting solution was allowed to reach room temperature overnight. The reaction was quenched with 1 M HCl (20 mL). The organic layer was diluted with ethyl acetate and washed with 37% NH_3 (10 mL), brine (20 mL), and water (2 × 20 mL). After drying over $MgSO_4$, the solvent was evaporated. Chromatography (silica gel, toluene, R_f 0.3) gave (*S*,*S*)-**7b** as a white solid (490 mg, 62%). $[\alpha]_D^{20}$ = +13 (*c* 1, $CHCl_3$). ^{31}P NMR ($CDCl_3$): δ 8.1 (br q, 2P). ^{1}H NMR ($CDCl_3$): δ 6.89 (m, 4H, Ar*H*), 2.49 (s, 12H, 4CH_3), 2.29 (s, 6H, 2CH_3), 1.75−1.49 (m, 4H, 2CH_2), 1.66 (d, 6H, 2CH_3, $J_{P,H}$ = 6.2 Hz), 1.25−0.47 (br, 6H, 2BH_3). MS *m*/*z* (FAB$^+$): 385 (M^+, 79) 371 (M^+ − BH_3, 100), 359 (M^+ − 2BH_3, 43), 240 (M^+ − 2BH_3 − Mes, 29). Anal. Calcd for $C_{22}H_{38}B_2P_2$: C, 68.44; H, 9.92. Found: C, 68.20; H, 9.77.

(*S*,*S*)-1,2-Bis(mesitylmethylphosphino)ethane, (*S*,*S*)-8b. (*S*,*S*)-1,2-Bis(mesitylmethylphosphino)ethane diborane, (*S*,*S*)-**7b**, (490 mg, 1.27 mmol) was dissolved in morpholine (6 mL). The solution was stirred for 24 h at room temperature and then evaporated to dryness at room temperature. Chromatography (alumina, toluene) under argon gave pure (*S*,*S*)-**8b** (392 mg, 86%). The enantiomeric excess (37% ee) was determined, as described below. ^{31}P NMR ($CDCl_3$): δ −39.1 (s, 2P). ^{1}H NMR ($CDCl_3$): δ 6.84 (m, 4H, Ar*H*), 2.50 (s, 12H, 4CH_3), 2.25 (s, 6H, 2CH_3), 1.89−1.79 (m, 4H, 2CH_2), 1.42 (d, 6H, 2CH_3, $J_{P,H}$ = 6.4 Hz). MS *m*/*z* (FAB$^+$): 359 (M^+, 100), 343 (M^+ − CH_3, 39), 239 (M^+ − Mes, 40). Anal. Calcd for $C_{22}H_{32}P_2$: C, 73.73; H, 9.00. Found: C, 73.42; H, 8.91.

(*R*,*R*)-Bis(1,2-(*P*-oxo-mesitylmethylphosphino)ethane, (*R*,*R*)-9b. An excess of H_2O_2 (30%, 2 mL) was added to a THF solution (2 mL) of (*S*,*S*)-**8b** (20 mg, 0.056 mmol). After stirring for 15 min, H_2O (5 mL) was added, the THF was evaporated, and the product was extracted with CH_2Cl_2. Evaporation of the solvent gave (*R*,*R*)- **9b** as a white oil (21.6 mg, 99%). ^{31}P NMR ($CDCl_3$): δ 43.55 (s, 2P). The addition of (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol (4 equiv vs **9b**) gave separate signals for (*R*,*R*)-**9b** and (*S*,*S*)-**9b**. (*R*,*R*)-**9b** ^{31}P NMR ($CDCl_3$): δ 47.09 (s, 2P, 68.4%). (*S*,*S*)-**9b** ^{31}P NMR ($CDCl_3$): δ 47.21 (s, 2P, 31.6%). 37% ee.

(*R*,*R*)- + (*S*,*S*)-1,2-Bis(mesitylmethylphosphino)ethane Diborane, (*l*)-7b. A 1.3 M hexane solution of *s*-BuLi (2.5 mL, 3.19 mmol) was added slowly to a solution of P(Me)$_2$(Mes)-(BH_3) (0.562 g, 2.896 mmol) in THF (10 mL) cooled at −78 °C. The reaction solution was warmed to −10 °C during 3 h and then cooled to −78 °C. A suspension of $CuCl_2$ (1.164 g, 8.69 mmol) in THF (10 mL) was added slowly by cannula, and the resulting solution was allowed to reach room temperature overnight. Workup (as for (*S*,*S*)-**7b**) gave (*l*)-**7b** (335 mg, 60%) and (*u*)-**9b** (84 mg, 15%). Diastereomerically pure (*l*)-**9b** was obtained by crystallization from hexane/ethyl acetate 5:1. (*l*)-**9b** has the same analytic properties as (*S*,*S*)-**9b**.

(*R*,*R*)- + (*S*,*S*)-1,2-Bis(mesitylmethylphosphino)ethane, (*l*)-8b. Same preparation and analytic properties as those given for (*S*,*S*)-**8b.**

(*R*,*R*)- + (*S*,*S*)-1,2-Bis(*P*-oxo-mesitylmethylphosphino)-ethane, (*l*)-9b. The racemic phosphine oxide (*l*)-**9b** was prepared from (*l*)-**8b** with the same procedure used for (*R*,*R*)-**9b**. ^{31}P NMR ($CDCl_3$): δ 43.55 (s, 2P). The addition of (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol (4 equiv vs (*l*)-**9b**) gave separate signals for (*R*,*R*)-**9b** and (*S*,*S*)-**9b**. (*R*,*R*)-**9b** ^{31}P NMR ($CDCl_3$): δ 47.67 (s, 2P, 50%). (*S*,*S*)-**9b** ^{31}P NMR: δ 47.81 (s, 2P, 50%).

9-Anthryldimethylphosphine Borane, 6c. A 3 M Et_2O solution of methylmagnesium chloride (48 mL, 0.143 mol) was added slowly to 9-anthryldichlorophosphine (20 g, 0.072 mol) in THF (500 mL) at −50 °C, and the solution was stirred overnight to reach room temperature. BH_3·SMe_2 (20.5 mL, 0.216 mol) was slowly added. After stirring for 3 h, the solvent was evaporated, and the crude product was extracted with toluene. Recrystallization from hexane/ethyl acetate 4:1 gave **6c** as a yellow solid (18.04 g, 99%, 0.071 mol). ^{31}P NMR ($CDCl_3$): δ −5.9 (br q, 1P). ^{1}H NMR ($CDCl_3$): δ 8.94 (m, 2H, Ant*H*), 8.61 (s, 1H, Ant*H*), 8.05 (m, 2H, Ant*H*), 7.62 (m, 2H, Ant*H*), 7.52 (m, 2H, Ant*H*), 2.05 (d, 6H, 2CH_3, $J_{P,H}$ = 9.6 Hz), 1.95−1.24 (br, 3H, BH_3). MS *m*/*z* (FAB$^+$): 237 ($M^+ - BH_3$, 100), 221 ($M^+ - BH_3 - CH_3$, 39), 207 ($M^+ - BH_3 - 2CH_3$, 17).

(*S*,*S*)-(+)-1,2-Bis(9-anthrylmethylphosphino)ethane Diborane, (*S*,*S*)-7c. A hexane solution of *s*-BuLi (1.7 mL, 2.2 mmol, 1.3 M) was added slowly to a solution of (−)-sparteine (0.5 mL, 0.511 g, 2.2 mmol) in THF (6 mL) cooled at −78 °C. After stirring for 15 min, a solution of **6c** (0.500 g, 1.9 mmol) in THF (7 mL) cooled at −78 °C was added slowly to the first solution. The mixture was then stirred for 3 h at −78 °C. A suspension of $CuCl_2$ (0.800 g, 5.95 mmol) in THF (10 mL) was added slowly by cannula, and the resulting solution was allowed to reach room temperature overnight. The reaction was quenched with 1 M HCl (10 mL) and diluted with ethyl acetate. The organic layer was washed with NH_3 37% (6 mL), brine (10 mL), and water (2 × 10 mL). After drying with $MgSO_4$, the solvent was evaporated. The crude product was purified by chromatography (silica gel, hexane/ethyl acetate 5:1, R_f 0.5) and isolated as a 6:1 mixture of the diastereoisomers (*l*)-**7c** and (*u*)-**7c** (690 mg, 70%). Pure (*S*,*S*)-**7c** was crystallized as a yellow solid from CH_2Cl_2/Et_2O 1:1 (385 mg, 39%). $[\alpha]_D^{20}$ = +11.3 (*c* 0.25, $CHCl_3$). ^{31}P NMR ($CDCl_3$): δ 14.8 (br q, 2P). ^{11}B NMR ($CDCl_3$): δ 35.6 (d, 2B, $J_{P,B}$ = 60 Hz). ^{1}H NMR ($CDCl_3$): δ 8.44 (m, 2H, Ant*H*), 8.26 (s, 1H, Ant*H*), 7.99 (m, 2H, Ant*H*), 7.47 (m, 2H, Ant*H*), 7.25 (m, 2H, Ant*H*), 2.14 (m, 4H, 2CH_2), 1.68 (d, 6H, 2CH_3, $J_{P,H}$ = 8.3 Hz), 1.72−0.94 (br, 3H, BH_3). MS *m*/*z* (FAB$^+$): 486 ($M^+ - BH_3$, 15), 472 ($M^+ - 2BH_3$, 38), 251 ($M^+ - 2BH_3 - P(Ant)(CH_3)$, 93). Anal. Calcd for $C_{32}H_{34}P_2B_2$: C, 76.54; H, 6.82. Found: C, 76.48; H, 6.61.

(*S*,*S*)-1,2-Bis(9-anthrylmethylphosphino)ethane, (*S*,*S*)-8c. (*S*,*S*)-**7c** (200 mg, 0.4 mmol) was dissolved in morpholine (8 mL), and the solution was stirred for 24 h at room temperature and then evaporated to dryness at room temperature. A short column of alumina in toluene under argon gave pure (*S*,*S*)-**8c** as a yellow solid (166 mg, 88%). The enantiomeric excess (18% ee) was determined as described below. ^{31}P NMR ($CDCl_3$): δ −27.3 (s, 2P). ^{1}H NMR ($CDCl_3$): δ 8.52 (m, 2H, Ant*H*), 8.21 (s, 1H, Ant*H*), 8.02 (m, 2H, Ant*H*), 7.67 (m, 2H, Ant*H*), 7.53 (m, 2H, Ant*H*), 2.23 (m, 4H, 2CH_2), 1.61 (d, 6H, 2CH_3, $J_{P,H}$ = 8.3 Hz). MS *m*/*z* (FAB$^+$): 472 (M^+, 68), 295 (M^+ − Ant, 23). Anal. Calcd for $C_{32}H_{28}P_2$: C, 81.00; H, 5.95. Found: C, 81.26; H, 5.66.

(*R*,*R*)-1,2-Bis(*P*-oxo-9-anthrylmethylphosphino)ethane, (*R*,*R*)-9c. An excess of H_2O_2 (30%, 2 mL) was added to (*S*,*S*)-**8c** (20 mg, 0.04 mmol) in THF (2 mL). After stirring for 15 min, H_2O (5 mL) was added, the THF was evaporated, and the product was extracted with CH_2Cl_2. Evaporation of the solvent gave (*R*,*R*)-**9c** as a yellow powder (19.7 mg, 99%). ^{31}P NMR ($CDCl_3$): δ 42.2 (s, 2P). The addition of (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol (2 equiv vs **9c**) gave (*R*,*R*)- **9c** and (*S*,*S*)- **9c**. (*R*,*R*)- **9c** ^{31}P NMR ($CDCl_3$): δ 45.28 (s, 2P, 59.1%). (*S*,*S*)- **9c** ^{31}P NMR ($CDCl_3$): δ 45.19 (s, 2P, 40.9%). 18% ee.

(*R*,*R*)- + (*S*,*S*)-1,2-Bis(9-anthrylmethylphosphino)ethane Diborane, (*l*)-7c. A hexane solution of *s*-BuLi (0.65 mL, 0.8 mmol, 1.3 M) was added slowly to a solution of **6c** (0.194 g, 0.8 mmol) in THF (3 mL) cooled at −78 °C. The mixture was then stirred for 3 h at −78 °C. A suspension of $CuCl_2$ (0.311 g, 2.3 mmol) in THF (5 mL) was added slowly by cannula, and the resulting solution was allowed to reach room temperature overnight. Workup was as for (*S*,*S*)-**7c**. Chromatography (silica gel, hexane/ethyl acetate 7:1, R_f 0.35) yielded (*l*)-**7c** (114 mg, 57%, 0.3 mmol) and some (*u*)-**7c** (30 mg, 15%). ^{31}P NMR ($CDCl_3$): δ 14.8 (br q, 2P). ^{11}B NMR ($CDCl_3$): δ 35.6 (d, 2B, $J_{P,B}$ = 60 Hz). ^{1}H NMR ($CDCl_3$): δ 8.44 (m, 2H, Ant*H*), 8.26 (s, 1H, Ant*H*), 7.99 (m, 2H, Ant*H*), 7.47 (m, 2H, Ant*H*), 7.25 (m, 2H, Ant*H*), 2.14 (m, 4H, 2CH_2), 1.68 (d, 6H, 2CH_3, $J_{P,H}$ = 8.3 Hz), 1.72−0.94 (br, 3H, BH_3).

(*R*,*R*)- + (*S*,*S*)-1,2-Bis(9-anthrylmethylphosphino)ethane, (*l*)-8c. Same preparation and analytic properties as those given for (*S*,*S*)-**8c**.

(*R*,*R*)- + (*S*,*S*)-1,2-Bis(*P*-oxo-9-anthrylmethylphosphino)ethane, (*l*)-9c. The racemic phosphine oxide was prepared from (*l*)-**8c** with the same procedure used for (*R*,*R*)-**9c**. ^{31}P NMR ($CDCl_3$): δ 43.55 (s, 2P). The addition of (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol (4 equiv vs (*l*)-**9c**) gave separate signals for (*R*,*R*)-**9c** and (*S*,*S*)-**9c**. (*R*,*R*)-**9c** ^{31}P NMR ($CDCl_3$): δ 45.28 (s, 2P, 50%); (*S*,*S*)-**9c** ^{31}P NMR ($CDCl_3$): δ 45.19 (s, 2P, 50%).

(2*R*,4*R*)-2-Mesityl-4-phenyl-2,4-diphosphapentane Diborane, (2*R*,4*R*)-11. A 1.3 M hexane solution of *s*-BuLi (9.8 mL, 12.8 mmol) was added slowly to a solution of **6b** (2.26 g, 11.6 mmol) in THF (80 mL) cooled at −78 °C. The orange solution was allowed to reach −10 °C in 5 h. (*S*)-PCl(Ph)(Me)-(BH_3), (*S*)-**10**, was prepared in situ by slowly adding a 1 M solution of HCl in Et_2O (12 mL, 12 mmol) to a solution of (R_P)-(−)-*N*-methyl[(1*S*,2*R*)-(2-hydroxy-1-methyl-2-phenyl)ethyl]aminomethylphenylphosphine borane, (R_P)-**4a**, (1.75 g, 5.8 mmol) in toluene (60 mL) under stirring. After 1 h, the white salt was filtered off. The yield of the chlorophosphine borane (*S*)-**10** was found to be 99% by NMR spectroscopy (^{31}P NMR: δ 96 (br q, 1P)). The orange solution of (*R*)- and (*S*)-P(Mes)(CH$_2$-Li)(Me)(BH_3) (cooled at −78 °C) was slowly added to the colorless solution of (*S*)-**10** (cooled at −78 °C). The resulting solution was allowed to reach room temperature overnight and was then quenched with water (20 mL). The product was extracted with ethyl acetate and dried with $MgSO_4$. The ^{1}H and ^{31}P NMR spectra of the crude product indicate the

presence of two diasteromers in a 5:1 ratio. Evaporation of the solvent and chromatography (silica gel, toluene, R_f 0.35) gave (2*R*,2*R*)-**11** as a white solid (1.266 g, 66%). HPLC (OD, hexane/2-propanol 98:2): (2*R*,4*R*)/(2*S*,4*S*) = 92.7:7.3 ((2*R*,4*R*)-**11** = 11.96 min, (2*S*,4*S*)-**11** = 13.73 min). 85.6% ee. ^{31}P NMR ($CDCl_3$): δ 6.4 (br q, 1P), 9.5 (br q, 1P). ^{1}H NMR ($CDCl_3$): δ 7.43 (m, 5H, Ph*H*), 6.81 (m, 4H, *H*^{3}Mes, *H*^{5}Mes), 2.45 (s, 6H, 2C*H*$_3$), 2.28 (s, 3H, C*H*$_3$), 2.21 (m, 2H, C*H*$_2$), 1.94 (d, 3H, C*H*$_3$, $J_{P,H}$ = 9.5 Hz), 1.88 (d, 3H, C*H*$_3$, $J_{P,H}$ = 10.1 Hz), 1.29−0.82 (br, 6H, 2B*H*$_3$). ^{11}B NMR ($CDCl_3$): δ −29 (br d, 1B, $J_{P,B}$ = 59 Hz), −38 (br d, 1B, $J_{P,B}$ = 61 Hz). MS *m*/*z* (FAB$^+$): 329 (M$^+$, 25), 315 (M$^+$ − BH_3, 100), 303 (M$^+$ − 2BH_3, 97), 196 (M$^+$ − 2BH_3 − 2BH_3 − Ph, 96), 179 ($MesPCH_3^+$, 95), 137 ($PhPCH_3^+$, 83). Anal. Calcd for $C_{18}H_{30}B_2P_2$: C, 65.52; H, 9.16. Found: C, 65.38; H, 9.10.

(2*R*,4*R*)-2-Mesityl-4-phenyl-2,4-diphosphapentane, (2*R*,4*R*)-12. (2*R*,4*R*)-**11** (590 mg, 1.8 mmol) was dissolved in morpholine (8 mL), and the solution was stirred for 24 h at room temperature. After evaporating the solution to dryness at room temperature, chromatography under argon (alumina, toluene) gave (2*R*,4*S*)-**12** as a thick oil (443 mg, 82%). ^{31}P NMR ($CDCl_3$): δ −38.2 (d, 1P, $J_{P,P'}$ = 144 Hz), −50.2 (d, 1P, $J_{P,P'}$ = 144 Hz). ^{1}H NMR ($CDCl_3$): δ 7.47 (m, 5H, Ph*H*), 6.83 (m, 4H, *H*^{3}Mes, *H*^{5}Mes), 2.42 (s, 6H, 2C*H*$_3$), 2.27 (s, 3H, C*H*$_3$), 2.13 (m, 2H, C*H*$_2$), 1.92 (d, 3H, C*H*$_3$, $J_{P,H}$ = 9.5 Hz), 1.85 (d, 3H, C*H*$_3$, $J_{P,H}$ = 10.1 Hz). MS *m*/*z* (FAB$^+$): 303 (M$^+$, 93), 287 (M$^+$ − CH_3, 100), 179 ($MesPCH_3^+$, 84). Anal. Calcd for $C_{18}H_{24}P_2$·0.25C_7H_8: C, 72.91; H, 8.05. Found: C, 72.93; H, 7.98.

(2*S*,4*S*)-2-Mesityl-4-phenyl-2,4-diphosphapentane Diborane, (2*S*,4*S*)-11. A 1.3 M hexane solution of *s*-BuLi (1.98 mL, 2.58 mmol) was added slowly to a solution of **6b** (500 mg, 2.58 mmol) in THF (20 mL) cooled at −78 °C. The orange solution was allowed to reach −10 °C in 5 h. (*R*)-PCl(Ph)(Me)-(BH_3) was prepared in situ by slowly adding a 1 M solution of HCl in Et_2O (12 mL, 12 mmol) to a solution of (S_P)-*N*-methyl-[(1*R*,2*S*)-(2-hydroxy-1-methyl-2-phenyl)ethyl]aminomethylphenylphosphine borane, (S_P)-**4a**, (775 mg, 1.3 mmol) in toluene (60 mL) under stirring. Reaction conditions and workup as those described for (2*R*,4*R*)-**11** gave (2*S*,4*S*)-**11** (0.258 g, 66%). HPLC (OD, hexane/2-propanol 98:2): (2*S*,4*S*)/(2*R*,4*R*) = 91.2:8.8 ((2*R*,4*R*)-**11** = 11.96 min, (2*S*,4*S*)-**11** = 13.73 min). 82.3% ee. Same analytical properties as those given for (2*R*,4*R*)-**11**.

(2*S*,4*S*)-2-Mesityl-4-phenyl-2,4-diphosphapentane, (2*S*,4*S*)-12. (2*S*,4*S*)-**11** (0.200 mg, 0.61 mmol) was dissolved in morpholine (8 mL), and the solution was stirred for 24 h at room temperature. After evaporating the solution to dryness at room temperature, chromatography under argon (alumina, toluene) gave (2*S*,4*S*)-**12** as a thick oil (151 mg, 82%). Same analytical properties as those given for (2*R*,4*R*)-**12**.

[Rh(COD)((*S*,*S*)-8a)]BF_4, 13a. [$Rh(COD)_2$]BF_4 (57 mg, 0.139 mmol) and (*S*,*S*)-**8a** (50 mg, 0.139 mmol) were dissolved in THF (5 mL). After stirring for 12 h at room temperature, the solution was concentrated under vacuum (1 mL), and Et_2O was added. The resulting orange precipitate was filtered off, washed with Et_2O, and dried in a vacuum. The product was isolated as its water adduct **13a**·H_2O (53 mg, 81%). $[\alpha]_D^{20}$ = −92 (*c* 0.25, $CHCl_3$). ^{31}P NMR ($CDCl_3$, 162 MHz): δ 55.3 (d, $^1J_{Rh,P}$ = 148.9 Hz, 2P). ^{1}H NMR ($CDCl_3$): δ 7.3 (m, 10H, Ph*H*), 5.58, 4.22 (2 s br, 4H, 4 =C*H*), 2.69−2.46 (m, 4H, 2CH_2), 2.35, 1.69 (2 m, 8H, 4C*H*$_2$), 1.61 (s, 4H, H_2O), 1.25 (s, 18H, 6C*H*$_3$). MS *m*/*z* (FAB$^+$): 569 (M$^+$ − BF_4, 72), 461 (M$^+$ − BF_4 − COD, 100), 211 (M$^+$ − BF_4 − P−P, 23). Anal. Calcd for $C_{30}H_{44}BF_4P_2$-Rh·H_2O: C, 53.43; H, 6.87. Found: C, 53.21; H, 6.69.

[Rh(COD)((*S*,*S*)-8b)]BF_4, 13b. [$Rh(COD)_2$]BF_4 (34 mg, 0.084 mmol) and (*S*,*S*)-**8b** (30 mg, 0.084 mmol) were dissolved in THF (5 mL). After stirring for 12 h at room temperature, the solution was concentrated under vacuum (1 mL), and Et_2O was added. The resulting orange precipitate was filtered off, washed with Et_2O, and dried in a vacuum. The product was isolated as its water adduct **13a**·3H_2O (42 mg, 76%), as indicated by integration of the ^{1}H NMR spectrum. $[\alpha]_D^{20}$ = −9.5 (*c* 0.15, $CHCl_3$). ^{31}P NMR ($CDCl_3$, 162 MHz): δ 39.2 (d, $^1J_{Rh,P}$ = 145.1 Hz, 2P). ^{1}H NMR ($CDCl_3$): δ 6.9 (m, 4H, Mes*H*), 5.25 (s, 2H, CH_2Cl_2), 4.24, 3.65 (2 s br, 4H, 4 =C*H*), 2.79−2.49 (m, 4H, 2C*H*$_2$), 2.54−2.29, 1.85−1.57 (2 m, 8H, 4C*H*$_2$), 2.46 (s, 6H, 2C*H*$_3$), 2.29 (s, 12H, 4C*H*$_3$), 2.14 (d, 6H, 2C*H*$_3$, $J_{P,H}$= 7.4 Hz), 1.60 (s, 6H, 3*H*$_2$O). MS *m*/*z* (FAB$^+$): 569 (M$^+$ − BF_4, 83), 461 (M$^+$ − BF_4 − COD, 100). Anal. Calcd for $C_{30}H_{44}$-BF_4P_2Rh·CH_2Cl_2·3H_2O: C, 46.82; H, 6.59. Found: C, 47.41; H, 6.23.

[Rh(COD)((*S*,*S*)-8d)]BF_4, 13d. [$Rh(COD)_2$]BF_4 (82 mg, 0.201 mmol) and (*S*,*S*)-**8d** (100 mg, 0.201 mmol) were dissolved in THF (5 mL). After stirring for 15 h at room temperature, the solution was concentrated to 1 mL, and Et_2O was added. The resulting yellow precipitate was filtered off, washed with Et_2O, and dried in a vacuum (159 mg, 99%). $[\alpha]_D^{20}$ = −274 (*c* 0.41, $CHCl_3$). ^{31}P NMR ($CDCl_3$, 162 MHz): δ 51.6 (d, $^1J_{Rh,P}$ = 149.6 Hz, 2P). ^{1}H NMR ($CDCl_3$): δ 8.12 (m, 2H, Np*H*), 7.99−7.31 (m, 22H, Ar*H*), 4.90, 3.75 (2 s br, 4H, 4 =C*H*), 2.54−2.29, 1.85−1.57 (2 m, 8H, 4 C*H*$_2$). MS *m*/*z* (FAB$^+$): 709.2 (M$^+$ − BF_4, 100), 599.1 (M$^+$ − BF_4 − COD, 57). Anal. Calcd for $C_{42}H_{40}$-BF_4P_2Rh: C, 63.34; H, 5.06. Found: C, 62.84; H, 5.84.

[Rh(COD)((2*R*,4*R*)-12)]PF_6, 15. [RhCl(COD)]$_2$ (61 mg, 0.124 mmol) and NH_4PF_6 (40 mg, 0.248 mmol) were dissolved in THF (5 mL). A solution of (2*R*,4*R*)-**12** (75 mg, 0.248 mmol) in THF (6 mL) was added under argon. After stirring for 15 h at room temperature, the white precipitate was filtered off, and Et_2O was added. The resulting orange solution was filtered and dried in a vacuum to give **15** as an orange powder (110 mg, 68%). $[\alpha]_D^{20}$ = −49.3 (*c* 0.125, $CHCl_3$). ^{31}P NMR ($CDCl_3$): δ −10.6 (dd, 1P, $J_{P,Rh}$ = 95 Hz, $J_{P,P'}$ = 80 Hz), −22.0 (dd, 1P, $J_{P,Rh}$ = 95 Hz, $J_{P,P'}$ = 80 Hz), −150 (septet, 1P, *P*F_6, $J_{P,F}$ = 713 Hz). ^{1}H NMR ($CDCl_3$): δ 7.39 (m, 5H, Ph*H*), 6.85 (m, 4H, *H*^{3}Mes, *H*^{5}Mes), 4.22, 3.62 (2 s br, 4H, 4 =C*H*), 2.53 (m, 2H, C*H*$_2$), 2.41 (s, 6H, 2C*H*$_3$), 2.25 (s, 3H, C*H*$_3$), 2.38, 1.65 (2 m, 8H, 4C*H*$_2$), 2.03 (d, 3H, C*H*$_3$, $J_{P,H}$ = 11.3 Hz), 1.81 (d, 3H, C*H*$_3$, $J_{P,H}$ = 9.1 Hz). MS *m*/*z* (FAB$^+$): 527 (M$^+$ − PF_6 + CH_3, 100), 512 (M$^+$ − PF_6, 43), 405 (M$^+$ − PF_6 − COD, 14). Anal. Calcd for $C_{26}H_{36}F_6P_3Rh$: C, 47.43; H, 5.51. Found: C, 47.41; H, 5.66.

Catalytic Hydrogenation. The standard procedure was as follows: the substrate and the catalyst were dissolved in 10 mL of the solvent under argon. The solution was stirred for 15 min and then transferred via a steel capillary into a 180-mL thermostated glass reactor or a 50-mL stainless steel autoclave. The inert gas was then replaced by hydrogen (three cycles), and the pressure was set. After completion of the reaction (total reaction times 15−65 h), the conversion was determined by gas chromatography, and the product was recovered quantitatively after filtration of the reaction solution on a plug of silica to remove the catalyst. See the Supporting Information for analytical details concerning the determination of the enantiomeric excess of the products.

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Supporting Information Available: Analytical details of the determination of the enantiomeric purity (Figure S1) and energy-minimized conformations of **15** (Figure S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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