Notes

Stereoselective, Oxidative One-Carbon Degradation of Alkyl(dimethyl)phosphine-Boranes. Synthesis of Enantiomerically Enriched Secondary Phosphine-Boranes

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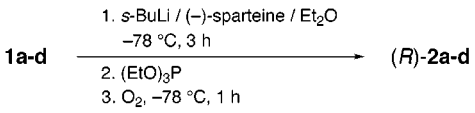
It has been demonstrated that some optically active phosphine ligands possessing a chiral center at the phosphorus exhibit excellent enantioselectivity in transition-metal-catalyzed asymmetric reactions.[1] This fact prompted us to develop new efficient methods for the synthesis of this class of phosphine ligands.[2] Previously, we reported that optically active phosphine-boranes having a P−H bond reacted with alkyl halides without significant racemization to give tertiary phosphine-boranes, precursors of chiral phosphines.[3] However, synthesis of the starting secondary phosphine-boranes[4] is not always readily accomplished; furthermore, the previously synthesized compounds are limited to those bearing at least one aromatic group.[5] We considered that enantiomerically enriched secondary phosphine-boranes might be obtained from readily available alkyl(dimethyl)-phosphine-boranes via stereoselective, oxidative one-carbon degradation.

Scheme 1 illustrates our idea, which involves a two-step transformation. The first step is an enantioselective conversion of alkyl(dimethyl)phosphine-boranes (**1**) to alkyl(hydroxymethyl)methylphosphine-boranes (**2**), and the second step is a stereospecific deformylation[6] or an oxidative degradation[7] leading to enantiomerically enriched secondary phosphine-boranes (**3**).

Table 1. Synthesis of Enantiomerically Enriched Alkyl(hydroxymethyl)methylphosphine-Boranes



substrate	R	yield, %	ee,[b] %
1a[a]	1-adamantyl	74	93[c] (99)[e]
1b	*tert*-butyl	73	91[c]
1c	cyclohexyl	70	75[c]
1d	phenyl	67	81[d]

[a] A mixed solvent (ether/toluene 3:1) was used. [b] Absolute configurations of **2a**−**d** assigned by analogy to refs 1f, 8. [c] The products were converted to the corresponding derivatives (Scheme 2), and their enantiomeric excesses were determined by HPLC analysis using Chiral Daicel columns. [d] The enantiomeric excess was determined by HPLC analysis using Chiral Daicel AS column. [e] The ee (%) value was obtained after recrystallization from hexane/ethyl acetate (10:1).

These transformations were examined using 1-adamantyl(dimethyl)phosphine-borane (**1a**), *tert*-butyl(dimethyl)phosphine-borane (**1b**), cyclohexyl(dimethyl)phosphine-borane (**1c**), and dimethyl(phenyl)phosphine-borane (**1d**). The first step was performed by enantioselective deprotonation by (−)-sparteine/*s*-BuLi,[1f,8] followed by oxidation with molecular oxygen[9] in the presence of triethyl phosphite. The results are summarized in Table 1. In all cases, the products were obtained in good yield and in considerably high enantioselectivity. The highest selectivity (93%) was observed in the reaction of **1a**, which bears the most bulky 1-adamantyl group. Recrystallization of the resulting compound **2a** (93% ee) from hexane/ethyl acetate (10:1) increased its enantiomeric excess to 99% ee. Other compounds **2b**−**d**, however, could not be recrystallized, because they were obtained as a pasty solid or an oil.

The second transformation was tested by the use of compound **2a** (99% ee). At first, the deformylation was examined in the presence of KOH at various tempera-

(1) For representative phosphine ligands in this class, see: (a) Vineyard, B. D.; Knowles, W. S.; Sabacky, M. J.; Bachman, G. L.; Weinkauff, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 5946−5952. (b) Robin, F.; Mercier, F.; Richard, L.; Mathey, F.; Spagnol, M. *Chem. Eur. J.* **1997**, *3*, 1365−1369. (c) Hamada, Y.; Matsuura, M.; Oku, M.; Hatano, K.; Shioiri, T. *Tetrahedron Lett.* **1997**, *38*, 8961−8964. (d) Dahlenburg, L.; Kurth, V. *Eur. J. Inorg. Chem.* **1998**, 597−603. (e) Stoop, R. M.; Mezzetti, A. *Organometallics* **1998**, *17*, 668−675. (f) Imamoto, T.; Watanabe, J.; Wada, Y.; Masuda, H.; Yamada, H.; Tsuruta, H.; Matsukawa, S.; Yamaguchi, K. *J. Am. Chem. Soc.* **1998**, *120*, 1635−1636. (g) Maienza, F.; Wörle, M.; Steffanut, P.; Mezzetti, A. *Organometallics* **1999**, *18*, 1041−1049. (h) Yamanoi, Y.; Imamoto, T. *J. Org. Chem.* **1999**, *64*, 2988−2989. (i) Tsuruta, H.; Imamoto, T. *Tetrahedron: Asymmetry* **1999**, *10*, 877−882. (j) Nettekoven, U.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Widhalm, M.; Spek, A. L.; Luts, M. *J. Org. Chem.* **1999**, *64*, 3996−4004.

(2) For a recent review, see: (a) Pietrusiewicz, K. M.; Zablocka, M. *Chem. Rev.* **1994**, *94*, 1375−1411. (b) Ohff, M.; Holz, J.; Quirmbach, M.; Börner, A. *Synthesis* **1998**, 1391−1415.

(3) (a) Imamoto, T.; Oshiki, T.; Onozawa, T.; Kusumoto, T.; Sato, K. *J. Am. Chem. Soc.* **1990**, *112*, 5244−5252. (b) Oshiki, T.; Imamoto, T. *J. Am. Chem. Soc.* **1992**, *114*, 3975−3977. (c) Imamoto, T.; Matsuo, M.; Nonomura, T.; Kishikawa, K.; Yanagawa, M. *Heteroatom. Chem.* **1993**, *4*, 475−486.

(4) (a) Oshiki, T.; Hikosaka, T.; Imamoto, T. *Tetrahedron Lett.* **1991**, *32*, 3371−3374. (b) Wolfe, B.; Livinghouse, T. *J. Am. Chem. Soc.* **1998**, *120*, 5116−5117.

(5) Recently, we have succeeded in synthesizing the enantiomerically enriched alkylmethylphosphine-boranes: Miura, T.; Yamada, H.; Kikuchi, S.; Imamoto, T. *J. Org. Chem.* **2000**, *65*, 1887−1880.

(6) The deformylation reaction has been reported for some hydroxymethylphosphines: (a) Ellis, J. W.; Harrison, K. N.; Hoye, P. A. T.; Orpen, A. G.; Pringle, P. G.; Smith, M. B. *Inorg. Chem.* **1992**, *31*, 3026−3033. (b) Cristau, H. J.; Virieux, D. *Tetrahedron Lett.* **1999**, *40*, 703−706.

(7) The decarboxylation procedure has been often employed for the preparation of P-chiral phosphines: (a) Bodalski, R.; Rutkowska-Olma, E.; Pietrusiewicz, K. M. *Tetrahedron* **1980**, *36*, 2353−2355. (b) Pietrusiewicz, K. M.; Zablocka, M.; Monkiewicz, J. *J. Org. Chem.* **1984**, *49*, 1522−1526. (c) Imamoto, T.; Sato, K.; Johnson, C. R. *Tetrahedron Lett.* **1985**, *26*, 783−786.

(8) Muci, A. R.; Campos, K. R.; Evans, D. A. *J. Am. Chem. Soc.* **1995**, *117*, 9075−9076.

(9) For representative reviews on the reaction of carbanion with molecular oxygen, see: (a) Jones, A. B. In *Encyclopedia of Reagents for Organic Synthesis*; Paquette, L. A., Ed.; Wiley: New York, 1995; Vol. 6, pp 3832−3836. (b) Jones, A. B. In *Comprehensive Organic Synthesis*, 1st ed.; Trost, B., Fleming, I., Ley, S. V., Eds.; Pergamon: Oxford, 1991; Vol. 7, pp 156−160. (c) Fuhrhop, J.; Penzlin, G. *Organic Synthesis*; VCH: Winheim, 1994.

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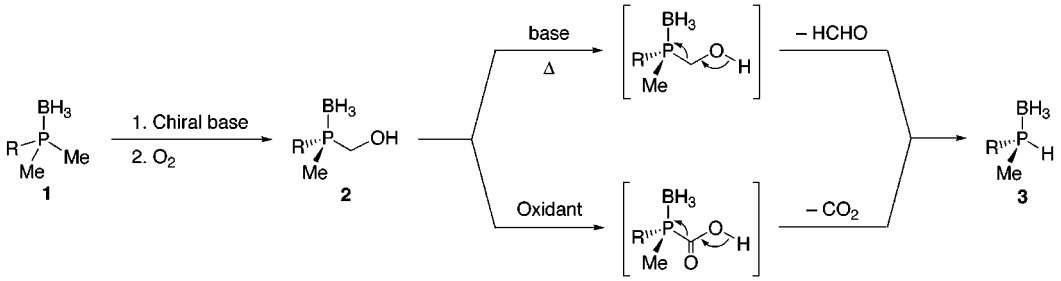
Scheme 1



Scheme 2

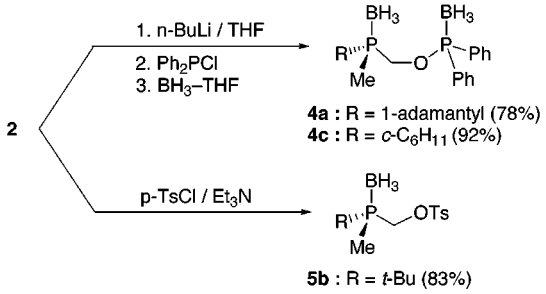
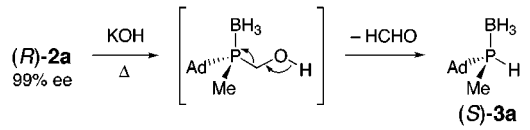


Table 2. Base-Promoted Deformylation of 2a[a]



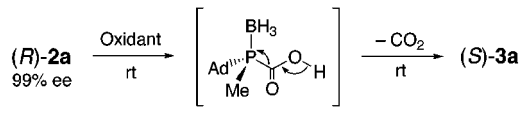
entry	temp, °C	time, h	yield, %	ee,[c] %
1	60	16	3 (93)[b]	
2	80	5	11 (88)[b]	93[d]
3	105	0.5	60 (34)[b]	45[d]
4	105	1	80	38[d]
5	105	2	71	7[d]
6	105	3	70	5[d]

[a] All reactions were carried out in toluene with a molar ratio of 1:3 (**2a**/KOH). [b] The values in parentheses indicate the yields of recoverd **2a**. [c] Absolute configuration of **3a** was determined by X-ray analysis of the corresponding 2-picolyl derivative, Ad(CH_3)-$PBH_3CH_2(C_5H_4N)$ (**6d**). [d] The ee (%) values were determined by HPLC analysis using Chiral Daicel OD-H column on the corresponding 2-picolyl derivative (**6d**).

tures. As shown in Table 2, the reaction at 60−80 °C was sluggish, affording the desired product in very low yield. On the other hand, the reaction proceeded rather smoothly at higher temperature (105 °C), but it was accompanied by significant racemization of the product, especially when the reaction mixture was heated for an extended period (entries 3−6).

Our attention was turned to oxidative degradation of the primary alcohol moiety. After screening of various oxidants and reaction conditions, we found that the ruthenium(VI)-catalyzed oxidation using $K_2S_2O_8$[10] afforded a satisfactory result in both chemical yield and stereospecificity (Table 3, entry 4). It is noted that the borane group remained unchanged under these oxidative conditions.[11] In a similar manner, **2b** (89% ee) was also converted to the corresponding secondary phosphine-borane (**3b**, 87% ee) in 79% yield.

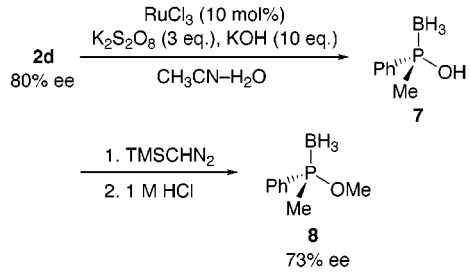
Table 3. Oxidative One-Carbon Degradation of 2a[a]



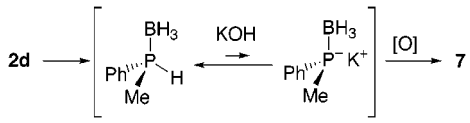
entry	conditions	yield, %	ee,[c] %
1	CrO_3 (3 equiv), H_2SO_4 aq/acetone, 5 h	22	97[d]
2	PDC (4 equiv)/DMF, 6 h	32	98[d]
3	$RuCl_3$ (1 mol%), $NaIO_4$/ $H_2O/CCl_4/CH_3CN$, 1 h	0[b]	
4	$RuCl_3$ (10 mol%), $K_2S_2O_8$ (3 equiv), KOH (10 equiv)/CH_3CN/H_2O, 2 h	91	99[d]

[a] All reactions were complete at ambient temperature within several hours. [b] The reaction proceeded rapidly, but it resulted in the formation of many products. [c] Absolute configuration of **3a** was determined by X-ray analysis of the corresponding 2-picolyl derivative, Ad(CH_3)$PBH_3CH_2(C_5H_4N)$ (**6d**). [d] The ee (%) values were determined by HPLC analysis using Chiral Daicel OD-H column on the corresponding 2-picolyl derivative (**6d**).

Scheme 3



Scheme 4



On the other hand, when this oxidation procedure was applied to compound **2d**, overoxidation took place to afford compound **7**,[12] which was assigned by conversion to the corresponding methyl ester **8** (Scheme 3).[13] This overoxidation is probably due to the rather acidic character of the initially formed secondary phosphine-borane possessing a phenyl group. Thus, as shown in Scheme 4,

(10) (a) Schröder, M.; Griffith, W. P. *J. Chem. Soc., Chem. Commun.* **1979**, 58−59. (b) Green, G.; Griffith, W. P.; Hollinshead, D. M.; Ley, S. V.; Schröder, M. *J. Chem. Soc., Perkin Trans. 1* **1984**, 681−686.

(11) Selective oxidation of the alcohol moiety of hydroxyalkylphosphine-boranes was reported: Pellon, P. *Tetrahedron Lett.* **1992**, *33*, 4451−4452.

(12) Compound **7** could not be sufficiently purified from the crude mixture, but it was assigned by HRMS (HRMS calcd for $C_7H_{12}BOP$ 154.0719, found 154.0712).

(13) Jugé et al. prepared (*S*)-methoxy(methyl)phenylphosphine-borane **8***s* ($[\alpha]_D$ −96 (*c* 5.0, $CHCl_3$)) from diastereomerically pure oxazaphospholidine-borane: (a) Jugé, S.; Stephan, M.; Laffitte, J. A.; Genêt, J. P. *Tetrahedron Lett.* **1990**, *31*, 6357−6360. (b) Uziel, J.; Stéphan, M.; Kaloun, El B.; Genêt, J. P.; Jugé, S. *Bull. Soc. Chim. Fr.* **1997**, *134*, 379−389.

this compound was subjected to deprotonation with KOH, and the generated phosphorus anion was readily oxidized under the conditions to give compound **7**.

In summary, we have shown that enantiomerically enriched secondary phosphine-boranes are obtained from alkyl(dimethyl)phosphine-boranes in two steps. The number of examples is limited, but this method may be applicable for the synthesis of other alkylmethylphosphine-boranes in enantiomerically enriched form.

Experimental Section

General. Diethyl ether, tetrahydrofuran (THF), and toluene were distilled from sodium/benzophenone ketyl under argon prior to use. 1-Adamantyl(dimethyl)phosphine-borane, *tert*-butyl(dimethyl)phosphine-borane, cyclohexyl(dimethyl)phosphine-borane, and dimethyl(phenyl)phosphine-borane (**1a**−**d**) were prepared according to the procedure described in the literature.[1f,8]

(*R*)-1-Adamantyl(hydroxymethyl)methylphosphine-Borane (2a). To a stirred, cooled (−78 °C) solution of (−)-sparteine (8.68 g, 37 mmol) in Et_2O (225 mL) was added *s*-BuLi (37.0 mL of a 1.0 M cyclohexane solution, 37 mmol) under Ar atmosphere. After 15 min, a solution of 1-adamantyl(dimethyl)-phosphine-borane (**1a**) (5.99 g, 29 mmol) in toluene (75 mL) was added dropwise, and the mixture was stirred at the same temperature. Three hours later, triethyl phosphite (2.38 g, 14 mmol) was added, and oxygen gas was blown through the solution with vigorous stirring. The mixture was stirred under O_2 atmosphere at the same temperature for 1 h, and the reaction was quenched by 1 M HCl. The organic layer was separated, and the aqueous layer was extracted with EtOAc. The combined organic layers were washed with brine and dried over Na_2SO_4. The solvent was evaporated on a rotary evaporator, and the residue was purified by flash chromatography on silica gel (toluene/$CHCl_3$, 1:1) to give **2a** as a white solid (4.79 g, 74%). An enantiomerically pure product was obtained by recrystallization from a mixed solvent of hexane/EtOAc (10:1) as colorless needles: mp 129−130 °C; $[\alpha]^{26}_D$ −4.8 (*c* 1.1, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.35 (br q, J_{HB} = 105.8 Hz, 3 H), 1.22 (d, $^2J_{HP}$ = 10.1 Hz, 3 H), 1.95 (s, 1 H), 1.72−2.04 (m, 15 H), 3.91 (d, J_{HH} = 13.0 Hz, 1 H), 4.07 (d, J_{HH} = 13.0 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.5 (d, J_{CP} = 35.3 Hz), 27.4−27.6 (m), 30.1 (d, J_{CP} = 32.8 Hz), 36.1−36.4 (m), 56.0 (d, J_{CP} = 37.7 Hz); IR (KBr) 3450, 2910, 2360, 1450, 1070 cm^{-1}; FAB MS (rel intensity) 225 (M^+ − H, 100), 195 (M^+ − CH_2OH, 91). Anal. Calcd for $C_{12}H_{24}BOP$: C, 63.74; H, 10.70. Found: C, 63.53; H, 10.77.

(*R*)-*tert*-Butyl(hydroxymethyl)methylphosphine-Borane (2b). To a stirred, cooled (−78 °C) solution of (−)-sparteine (10.7 g, 46 mmol) in Et_2O (100 mL) was added *s*-BuLi (46.0 mL of a 1.0 M cyclohexane solution, 46 mmol) under Ar atmosphere. After 15 min, a solution of *tert*-butyl(dimethyl)-phosphine-borane (**1b**) (4.62 g, 35 mmol) in Et_2O (100 mL) was added dropwise, and the mixture was stirred at −78 °C. Three hours later, triethyl phosphite (2.99 g, 18 mmol) was added, and oxygen gas was blown through the solution with vigorous stirring. The mixture was kept at −78 °C under O_2 atmosphere for 1 h, and the reaction was quenched by 1 M HCl. The organic layer was separated, and the aqueous layer was extracted with EtOAc. The combined organic layers were washed with brine and dried over Na_2SO_4. The solvent was evaporated on a rotary evaporator, and the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 3:1) to give **2b** as a pasty solid (3.77 g, 73%): mp 157−160 °C; $[\alpha]^{28}_D$ −9.8 (91% ee, *c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.39 (qd, J_{HB} = 99.3 Hz, $^2J_{HP}$ = 14.0 Hz, 3 H), 1.21 (d, $^3J_{HP}$ = 13.5 Hz, 9 H), 1.27 (d, $^2J_{HP}$ = 10.1 Hz, 3 H), 2.05 (s, 1 H), 3.96 (d, J_{HH} = 13.3 Hz, 1 H), 4.05 (d, J_{HH} = 13.3 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 3.0 (d, J_{CP} = 34.4 Hz), 25.4 (d, $^2J_{CP}$ = 10.6 Hz), 27.2 (d, J_{CP} = 32.0 Hz), 57.0 (d, J_{CP} = 37.7 Hz); IR (KBr) 3480, 2970, 2380, 1070, 910 cm^{-1}. Anal. Calcd for $C_6H_{18}BOP$: C, 48.70; H, 12.26. Found: C, 48.84; H, 12.31.

(*R*)-Cyclohexyl(hydroxymethyl)methylphosphine-Borane (2c). This compound was prepared from **1c** (474 mg, 3 mmol) according to the procedure described for the preparation of **2a**. After workup, the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 3:1) to give **2c** as a colorless oil (367 mg, 70%): $[\alpha]^{25}_D$ −1.9 (75% ee, *c* 1.6, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.39 (br q, J_{HB} = 104.4 Hz, 3 H), 1.27 (d, $^2J_{HP}$ = 10.5 Hz, 3 H), 1.19−1.86 (m, 11 H), 2.18 (s, 1 H), 3.97 (s, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 4.0 (d, J_{CP} = 36.1 Hz), 25.7, 26.0, 26.2, 26.3−26.4, 31.2 (d, J_{CP} = 33.6 Hz), 57.4 (d, J_{CP} = 39.4 Hz); IR (neat) 3480, 2930, 2370, 1450, 1070 cm^{-1}; HRMS calcd for $C_8H_{20}BOP$ 174.1345, found 174.1351.

(*R*)-Hydroxymethyl(methyl)phenylphosphine-Borane (2d). This compound was prepared from **1d** (3.04 g, 20 mmol) according to the procedure described for the preparation of **2a**. After workup, the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 3:1) to give **2d** as a colorless oil (2.32 g, 69%). Separation of enantiomers by chiral HPLC (Daicel Chiralcel AS, flow rate 0.75 mL/min, 10% 2-PrOH/hexane, (*R*) t_1 = 15.1 min; (*S*) t_2 = 17.9 min) determined the ee to be 81%: $[\alpha]^{25}_D$ −7.2 (81% ee, *c* 1.2, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.35 (br q, J_{HB} = 104.1 Hz, 3 H), 1.63 (d, $^2J_{HP}$ = 10.6 Hz, 3 H), 2.47 (s, 1 H), 4.06 (s, 2 H), 7.46−7.55 (m, 3 H), 7.73−7.77 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 6.9 (dq, J_{CP} = 38.6 Hz, $^2J_{CB}$ = ca. 10 Hz), 60.7 (d, J_{CP} = 41.0 Hz), 127.0 (d, J_{CP} = 53.3 Hz), 128.8, 131.7−131.9 (m); IR (neat) 3470, 2370, 1440, 1070, 910 cm^{-1}; HRMS calcd for $C_8H_{14}BOP$ 168.0875, found 168.0869.

(*R*)-[(1-Adamantyl(boranato)methylphosphino)methyloxy]diphenylphosphine-Borane (4a). To a stirred solution of (*R*)-1-adamantyl(hydroxymethyl)methylphosphine-borane (**2a**) (113 mg, 0.5 mmol) in THF (2 mL) was slowly added *n*-BuLi (0.33 mL of a 1.52 M hexane solution) at 0 °C under Ar atmosphere. After 15 min, chlorodiphenylphosphine (0.13 mL, 0.75 mmol) was added dropwise, and the mixture was gradually warmed to room temperature during 1 h. The flask was cooled to 0 °C again, and BH_3−THF complex (1.2 mL of a 1 M THF solution) was added. One hour later, the reaction mixture was treated with 1 M HCl. 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 dried over Na_2SO_4. The solvent was removed on a rotary evaporator, and the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 5:1) to give product **4a** as a colorless oil that solidified on standing (167 mg, 79%). The product was recrystallized from hexane/MeOH (1:5) to give colorless needles: mp 112−114 °C; $[\alpha]^{27}_D$ −0.4 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.0−1.4 (m, 6 H), 1.27 (d, $^2J_{HP}$ = 9.9 Hz, 3 H), 1.57−2.00 (m, 15 H), 4.12 (dd, J_{HH} = 12.8 Hz, $^2J_{HP}$ = 5.3 Hz, 1 H), 4.37 (dd, J_{HH} = 12.8 Hz, $^2J_{HP}$ = 5.0 Hz, 1 H), 7.47−7.56 (m, 6 H), 7.73−7.77 (m, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.6 (d, J_{CP} = 35.3 Hz), 27.5 (d, $^2J_{CP}$ = 9.0 Hz), 30.6 (d, J_{CP} = 32.0 Hz), 36.2, 59.7 (d, J_{CP} = 36.9 Hz), 128.8−128.9 (m), 130.2 (d, J_{CP} = 23.0 Hz), 130.8 (d, J_{CP} = 24.6 Hz), 131.3−131.5 (m), 132.4−132.5 (m); IR (KBr) 2900, 2390, 1440, 1030 cm^{-1}; FAB MS (rel intensity) 423 (M^+ − H, 42), 409 (M^+ − BH_3 − H, 100). Anal. Calcd for $C_{24}H_{36}B_2OP_2$: C, 67.97; H, 8.56. Found: C, 68.01; H, 8.74.

(*R*)-[(Boranato(cyclohexyl)methylphosphino)methyloxy]-diphenylphosphine-Borane (4c). This compound was prepared from **2c** (1.22 g, 7 mmol) according to the procedure described for the preparation of the 1-adamantyl substituted compound. After workup, the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 5:1) to give product **(4c)** as a colorless oil (2.40 g, 92%): $[\alpha]^{27}_D$ −7.3 (70% ee, *c* 1.4, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.1−1.0 (m, 6 H), 1.32 (d, $^2J_{HP}$ = 10.1 Hz, 3 H), 1.20−1.87 (m, 11 H), 4.13 (dd, J_{HH} = 13.0 Hz, $^2J_{HP}$ = 5.1 Hz, 1 H), 4.30 (dd, J_{HH} = 13.0 Hz, $^2J_{HP}$ = 5.6 Hz, 1 H), 7.47−7.59 (m, 6 H), 7.70−7.75 (m, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 4.7 (d, J_{CP} = 36.1 Hz), 25.6, 26.0, 26.1, 26.2−26.3, 31.1 (d, J_{CP} = 34.5 Hz), 60.4 (d, J_{CP} = 37.0 Hz), 128.8−128.9 (m), 130.2 (d, J_{CP} = 10.6 Hz), 130.8 (d, J_{CP} = 10.7 Hz), 131.2−131.4 (m), 132.4; IR (neat) 2940, 2380, 1440, 1030 cm^{-1}; HRMS calcd for $C_{20}H_{32}B_2OP_2$ 372.2114, found 372.2124.

(*R*)-*tert*-Butylmethyl(*p*-toluenesulfonyloxymethyl)phosphine-Borane (5b). To a stirred, cooled (0 °C) solution of (*R*)-*tert*-butyl(hydroxymethyl)methylphosphine-borane (**2b**) (444 mg, 3 mmol) in triethylamine (4.5 mL) was added *p*-toluenesulfonyl chloride (1.14 g, 6 mmol) in one portion, and the mixture was vigorously stirred at room temperature. One hour later, the reaction mixture was treated with 1 M HCl. 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 dried over Na_2SO_4. The solvent was removed on a rotary evaporator, and the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 5:1) to give product (**5b**) as a white solid (750 mg, 83%). An enantiomerically pure product was obtained as colorless needles by recrystallization from hexane: mp 81−83 °C; $[\alpha]^{28}_D$ −13.5 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.29 (br q, J_{HB} = 103.7 Hz, 3 H), 1.19 (d, $^3J_{HP}$ = 14.5 Hz, 9 H), 1.33 (d, $^2J_{HP}$ = 9.9 Hz, 3 H), 2.48 (s, 3 H), 4.15 (d, J_{HH} = 13.0 Hz, 1 H), 4.40 (d, J_{HH} = 13.0 Hz, 1 H), 7.40 (d, $^3J_{HH}$ = 7.7 Hz, 2 H), 7.80 (d, $^3J_{HH}$ = 8.5 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 2.8 (d, J_{CP} = 34.9 Hz), 21.7, 25.5, 27.9 (d, J_{CP} = 31.2 Hz), 63.0 (d, J_{CP} = 28.7 Hz), 128.1, 130.2, 131.3, 145.8; IR (KBr) 2970, 2400, 2370, 1600, 1370 cm^{-1}; FAB MS (rel intensity) 301 (M^+ − H, 68), 289 (M^+ − BH_3 + H, 21), 117 (M^+ − CH_2OTs, 100). Anal. Calcd for $C_{13}H_{24}BO_3PS$: C, 51.67; H, 8.01. Found: C, 51.74; H, 7.85.

(*S*)-1-Adamantylmethylphosphine-Borane (3a). To a stirred, cooled (0 °C) solution of potassium hydroxide (3.36 g, 60 mmol) and potassium persulfate (4.86 g, 18 mmol) in water (36 mL) was added ruthenium trichloride trihydrate (156 mg, 0.6 mmol). After 15 min, a solution of (*R*)-1-adamantyl(hydroxymethyl)methylphosphine-borane (**2a**) (99% ee, 1.36 g, 6 mmol) in acetonitrile (18 mL) was added dropwise, and the mixture was vigorously stirred at room temperature. Two hours later, the reaction mixture was treated 1 M HCl. The organic layer was separated, and the aqueous layer was extracted with ether three times. The combined organic layers were filtered through a Celite pad to remove any residual ruthenium, washed with brine, and dried over Na_2SO_4. The solvent was removed on a rotary evaporator, and the residue was purified by flash chromatography on silica gel ($CHCl_3$) to give the desired product (**3a**) (1.04 g, 89%). The product was converted to 2-picolyl derivative, and its enantiomeric excess was determined to be 99% by HPLC analysis. This compound was recrystallized from hexane to give colorless needles: mp 62−63 °C; $[\alpha]^{27}_D$ +6.8 (99% ee, *c* 1.0, $CHCl_3$) [lit.[5] mp 64−65 °C; $[\alpha]^{27}_D$ +6.2 (*c* 1.0, $CHCl_3$)]; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.45 (br q, J_{HB} = 92.1 Hz, 3H), 1.26 (dd, J_{HP} = 10.6 Hz, J = 6.0 Hz, 3H), 1.68−1.88 (m, 12H), 2.05 (br s, 3H), 4.21 (dm, J_{HP} = 355.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 0.1 (dd, J = 35.7, 8.2 Hz), 27.2−27.6 (m), 28.6 (d, J_{CP} = 37.0 Hz), 35.9−36.2 (m), 37.3−37.6 (m); ^{31}P NMR (160 MHz, $CDCl_3$) δ 8.3−9.6 (m); IR (NaCl plates) 2900, 2380, 1450 cm^{-1}; MS (FAB) *m*/*z* 195 (M^+ − H), Anal. Calcd for $C_{11}H_{22}BP$: C, 67.38; H, 11.31. Found: C, 67.24; H, 11.24.

(*S*)-*tert*-Butylmethylphosphine-Borane (3b). This compound was prepared from **2b** (89% ee, 296 mg, 2 mmol) according to the procedure described for the preparation of **3a**. After workup, the residue was purified by flash chromatography on silica gel ($CHCl_3$) to give **3b** as a colorless solid (186 mg, 79%). The product was converted to the 2-picolyl derivative,[5] and its enantiomeric excess was determined to be 87% by HPLC analysis: $[\alpha]^{27}_D$ +3.2 (87% ee, *c* 1.0, $CHCl_3$) [lit.[5] $[\alpha]^{28}_D$ +3.9 (*c* 2.2, $CHCl_3$)]; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.49 (br q, J_{HB} = 98.6 Hz, 3H), 1.20 (dd, J_{HP} = 14.7 Hz, J = 4.6 Hz, 9H), 1.30 (dd, J_{HP} = 10.9 Hz, J = 6.3 Hz, 3H), 4.41 (dm J_{HP} = 355.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 2.1 (d, J_{CP} = 35.3 Hz), 26.0 (d, J_{CP} = 34.1 Hz), 26.2 ($^2J_{CP}$ = 2.5 Hz); ^{31}P NMR (160 MHz, $CDCl_3$) δ 12.3−13.5 (m); IR (KBr) 2970, 2380, 1480 cm^{-1}; HRMS (EI) calcd for $C_5H_{15}BP$ (M^+ − H) 117.1005, found 117.1003.

(*S*)-1-Adamantylmethyl(2-picolyl)phosphine-Borane (6a). To a stirred solution of (*S*)-1-adamantylmethylphosphine-borane (**3a**) (98 mg, 0.5 mmol) in THF (2 mL) was slowly added *n*-BuLi (0.36 mL of a 1.52 M hexane solution) at −78 °C under Ar atmosphere. After 1 h, a solution of 2-picolyl chloride (96 mg, 0.75 mmol) in THF (1 mL) was added dropwise, and the mixture was gradually warmed to room temperature during 1 h. One hour later, the reaction mixture was treated with ice 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 dried over Na_2SO_4. The solvent was removed on a rotary evaporator, and the residue was purified by flash chromatography on silica gel (hexane/EtOAc, 3:1) to give product **6a** as a white solid (104 mg, 72%). An optically pure product was obtained by recrystallization from hexane as colorless needles: mp 109−113 °C; $[\alpha]^{28}_D$ −2.7 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.32 (br q, J_{HB} = 101.5 Hz, 3 H), 1.11 (d, $^2J_{HP}$ = 9.7 Hz, 3 H), 1.72−2.05 (m, 15 H), 3.10−3.25 (m, 2 H), 7.15−7.18 (m, 1 H), 7.36−7.38 (m, 1 H), 7.61−7.65 (m, 1 H), 8.48−8.49 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 3.3 (d, J_{CP} = 34.4 Hz), 27.6 (d, $^2J_{CP}$ = 8.2 Hz), 30.2 (d, J_{CP} = 27.0 Hz), 30.7 (d, J_{CP} = 32.8 Hz), 35.7, 36.4, 121.8, 125.5, 136.2, 148.9, 154.4; IR (KBr) 2900, 2370, 1590, 1440, 1060 cm^{-1}; FAB MS (rel intensity) 286 (M^+ − H, 100), 274 (M^+ − BH_3 + H, 17). Anal. Calcd for $C_{17}H_{27}BNP$: C, 71.10; H, 9.48; N, 4.88. Found: C, 70.95; H, 9.45; N, 4.87.

X-ray Crystallographic Analysis of 6a. Absolute configuration at the chiral phosphorus was determined to be *S* by single-crystal X-ray analysis. Crystallographic data for $Ad(CH_3)PBH_3$-$CH_2(C_5H_4N)$: $C_{17}H_{27}BNP$; orthorhombic, space group $P2_12_12$ (no. 18); Z = 4; D = 1.12 g cm^{-1}; cell constants a = 11.759(4), b = 21.757(4), c = 6.649(4) Å; V = 1700(1) Å^3; temperature of data collection 293 K; 3667 reflections measured, 1841 unique reflections ($I > 3.00\sigma(I)$); 181 variables; R = 0.074; Rw = 0.114; GOF = 2.60; Flack parameter = 0.037.

Enantiomeric Excess Determination. The following list describes conditions used for separation of racemic products: **[(1-adamantyl(boranato)methylphosphino)methyloxy]-diphenylphosphine-borane (4a)** (HPLC, Daicel Chiralcel OF, 0.25 mL/min, 10% 2-PrOH/hexane, (*R*) t_1 = 54.9 min; (*S*) t_2 = 60.9 min); **[(boranato(cyclohexyl)methylphosphino)methyloxy]diphenylphosphine-borane (4c)** (HPLC, Daicel Chiralcel OF, 0.75 mL/min, 10% 2-PrOH/hexane, (*R*) t_1 = 19.2 min; (*S*) t_2 = 23.9 min); ***tert*-butylmethyl(*p*-toluenesulfonyloxymethyl)phosphine-borane (5b)** (HPLC, Daicel Chiralcel OJ, 1.0 mL/min, 10% 2-PrOH/hexane, (*S*) t_1 = 16.9 min; (*R*) t_2 = 21.1 min); **1-adamantylmethyl(2-picolyl)phosphine-borane (6a)** (HPLC, Daicel Chiralcel OD-H, 0.50 mL/min, 10% 2-PrOH/hexane, (*R*) t_1 = 11.9 min; (*S*) t_2 = 15.1 min); ***tert*-butylmethyl-(2-picoryl)phosphine-borane**[5] (HPLC, Daicel Chiralcel AS, 0.50 mL/min, 10% 2-PrOH/hexane, (*S*) t_1 = 10.7 min; (*R*) t_2 = 11.8 min); and **methoxy(methyl)phenylphosphine-borane (8)** (HPLC, Daicel Chiralcel OJ, 0.50 mL/min, 10% 2-PrOH/hexane, (*R*) t_1 = 18.1 min; (*S*) t_2 = 20.0 min).

Compounds **2a**−**c**, **3a**, **3b**, and **7** were converted to the corresponding derivatives, and their enantiomeric excesses were determined by HPLC.

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Supporting Information Available: ^{1}H NMR spectra for selected compounds; an ORTEP plot for (*S*)-1-adamantylmethyl(2-picolyl)phosphine-borane (**6a**); and tables of crystal data, structure solution and refinement, atomic coordinates, bond lengths and angles. This material is available free of charge via the Internet at http://pubs.acs.org.

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