P-Chirogenic Phosphine/Sulfide Hybrid Ligands

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Received 31 July 2001

Abstract: P-Chirogenic phosphine/sulfide hybrid ligands **1** were prepared by the use of optically active phosphine-boranes as the intermediates. The palladium complexes of the ligands exhibited high catalytic activity and enantioselectivity in allylic alkylation of 1-acetoxy-1,3-diphenylprop-2-ene with malonate esters.

Key words: asymmetric catalysis, allylation, palladium, phosphorus, sulfur

Introduction

Optically active bidentate phosphine ligands have played an important role in transition metal-catalyzed asymmetric transformations, and numerous phosphine ligands have been designed and prepared to develop effective catalytic asymmetric processes.[1] The use of C_2 symmetric diphosphine ligands is one of the most powerful strategies for this purpose owing to their high stereodifferentiation ability and synthetic accessibility, and a great number of publications dealing with this type of ligands have appeared so far.[2] On the other hand, an increased attention has also been paid to the development of the bidentate ligands without C_2 symmetry in which two donor atoms play different roles from each other.[3] The hybrid type bidentate ligand, in which different heteroatoms are employed as two donor sites, is one of the representatives and has already been used in many transition metal-catalyzed asymmetric reactions with high efficiency.[4,5] One of the advantages of the hybrid ligands lies in high accessibility for structural tuning in both steric and electronic means. The structural diversity will realize various reactivity and stereoinduction ability.

Previously, we have designed and prepared C_2 symmetric diphosphine ligands with the chirogenic centers at the phosphorus atoms (abbreviated as BisP*[6] and MiniPHOS[7]). These ligands were proven to be quite effective in some transition metal-catalyzed asymmetric reactions. The non-C_2 symmetric version of BisP*, which possesses different substituent patterns on two phosphorus atoms, has also been prepared and employed in Rh-catalyzed asymmetric hydrogenation of dehydroamino acids.[8] The careful choice of substituent combination on two phosphorus atoms has provided high enantioselectivity even in the case of β,β-disubstituted dehydroamino acid derivatives. This fact intrigued us to develop the bidentate ligands with two different donor atoms in order to construct highly regulated chiral environment. We report here the preparation of novel optically active phosphine/sulfide hybrid bidentate ligands **1** containing a chirogenic center at a phosphorus atom and their stereoinduction ability in Pd-catalyzed asymmetric allylic substitution reaction.[9]

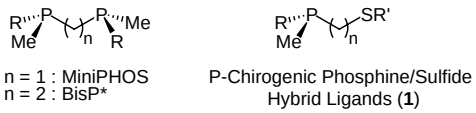


Figure Chemical Structures of C_2 symmetric diphosphine ligands MiniPHOS and BisP* and the P-chirogenic phosphine/sulfide hybrid ligands **1**

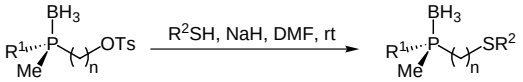
Preparation of P-Chirogenic Phosphine/Sulfide Hybrid Ligands

Synthetic routes to P-chirogenic P/S-hybrid ligands are shown in Schemes 1 and 2. Previously reported phosphine-borane procedure was employed to obtain these hybrid ligands. (*R*)-*tert*-Butylmethyl(*p*-toluenesulfonyloxymethyl)phosphine–borane (**2a**) and (*R*)-*tert*-butylmethyl-[2-(*p*-toluenesulfonyloxy)ethyl]phosphine–borane (**2b**) were prepared according to the reported procedure.[8a,10] (*R*)-Methylphenyl(*p*-toluenesulfonyloxymethyl)phosphine-borane (**2c**) was prepared from dimethylphenylphosphine–borane via enantioselective hydroxylation and subsequent tosylation.[10,11] The tosylates **2a**–**c** were treated with sodium thiolate in DMF at ambient temperature. The reactions were completed within 4 hours to give phosphine–boranes **3a**–**j** bearing sulfide functionality in excellent yield. Compounds **3c** and **3k** could be prepared also by a convenient procedure using disulfide (Scheme 2). Thus, alkyldimethylphosphine–boranes **4a**,**b** were directly converted into **3c**,**k** in one pot by successive reactions with *s*-BuLi/(–)-sparteine and phenyl disulfide.[10]

Trialkylphosphine–boranes **3a**,**c**–**k** were deboranated to give free phosphine/sulfides **1a**,**c**–**k** by treatment with trifluoromethanesulfonic acid in toluene, followed by KOH in ethanol–water (Scheme 3).[12] Compound **3b** that bears a phenyl group on the phosphorus atom was subjected to deboranation by treatment with 1-methylpyrrolidine to **1b**.[13] The phosphine/sulfides **1a**–**k** were purified by passing through a short alumina or silica gel column and used in the catalytic reactions without further purification.

Synthesis 2001, No. 15, 12 11 2001. Article Identifier:
1437-210X,E;2001,0,15,2348,2353,ftx,en;C04201SS.pdf.

ISSN 0039-7881

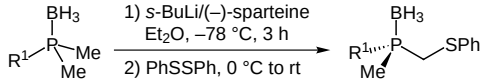


2a : R^1 = *t*-Bu, n = 1
2b : R^1 = *t*-Bu, n = 2
2c : R^1 = Ph, n = 1

3

	R^1	R^2	n	time / h	yield / %
3a	*t*-Bu	*t*-Bu	1	1.5	98
3b	Ph	*t*-Bu	1	3	85
3c	*t*-Bu	Ph	1	3	97
3d	*t*-Bu	Ph	2	3	96
3e	*t*-Bu	*o*-tolyl	1	3	96
3f	*t*-Bu	*p*-tolyl	1	3	89
3g	*t*-Bu	2-naphthyl	1	4	98
3h	*t*-Bu	*p*-NO_2-C_6H_4	1	14	26
3i	*t*-Bu	Cy	1	1.5	92
3j	*t*-Bu	Bn	1	3	93

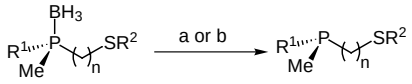
Scheme 1



4a : R^1 = *t*-Bu
4b : R^1 = 1-Ad

3c (R^1 = *t*-Bu) : 92 % yield
3k (R^1 = 1-Ad) : 69 % yield

Scheme 2



3a-k **1a-k**

a) (i) TfOH, toluene, 0 °C to rt, 1 h; (ii) KOH, EtOH/H_2O (10/1), 40 °C, 1 h; b) pyrrolidine, 50 °C, 2 h

Scheme 3

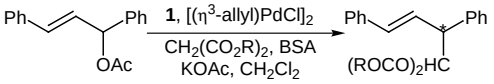
Pd-Catalyzed Asymmetric Allylic Alkylation

The phosphine/sulfide ligands **1** were employed in Pd-catalyzed asymmetric allylic alkylation of allylic acetate with carbon nucleophiles. The palladium complexes of phosphine/sulfides were generated in situ from di(μ-chloro)bis(η^3-allyl)dipalladium(II) and ligands **1**. The allylic alkylation was performed by mixing 1-acetoxy-1,3-diphenylprop-2-ene with dimethyl or di(*tert*-butyl) malonate, *N*,*O*-bis(trimethylsilyl)acetamide (BSA) and potassium acetate in the presence of Pd complex of **1**. The results are summarized in the Table.

The allylation of dimethyl malonate with Pd complex of **1a**, which has *tert*-butyl groups on both donor atoms, was sluggish and gave only 15% ee of allylation product in 73% yield (entry 1). Although ligand **1b**, that possesses phenyl group on phosphorus, provided higher reactivity, no enantioinduction was observed (entry 2). The use of Pd complex of **1c**, in which phenyl group is introduced on sulfur atom, showed high catalytic activity and enantioselectivity (entries 3 and 4). The reaction proceeded even at –40 °C to afford the allylation product in 94% yield. It is noteworthy that ligand **1d**, in which two donor atoms are bound to each other by ethylene chain, provided the (*S*)-configured products (entries 6–8). This opposite enantioselectivity is probably due to the formation of a 5-membered chelate ring structure.

Several types of substituent on sulfur atom were also examined (entries 9–15). Among them, phenyl group was found to be the best as a substituent on sulfur atom. Introduction of 1-adamantyl group on phosphorus atom resulted in high reactivity but rather slightly lower enantioselectivity than that of **1c** (entries 16 and 17). In each case, the reaction with di(*tert*-butyl) malonate showed relatively higher enantioselectivity (entries 5, 8 and 18).

Table Asymmetric Allylic Substitution of 1-Acetoxy-1,3-diphenylprop-2-ene with Malonate Esters Catalyzed by Pd Complexes of **1**[a]



Entry	Ligand	R	Time (h)	Yield (%)[b]	ee (%) (config)[c]
1	**1a**	Me	45	73	15 (*R*)
2	**1b**	Me	1.5	95	2 (*R*)
3	**1c**	Me	2	99	70 (*R*)
4[d]	**1c**	Me	36	94	85 (*R*)
5[d]	**1c**	*t*-Bu	60	99	90 (*R*)
6	**1d**	Me	1	99	53 (*S*)
7[d]	**1d**	Me	68	85	71 (*S*)
8[d]	**1d**	*t*-Bu	117	50	74 (*S*)
9	**1e**	Me	27	61	30 (*R*)
10	**1f**	Me	43	81	59 (*R*)
11[d]	**1f**	Me	85	33	80 (*R*)
12	**1g**	Me	24	39	22 (*R*)
13	**1h**	Me	22	39	40 (*R*)
14	**1i**	Me	22	58	44 (*R*)
15	**1j**	Me	13	90	48 (*R*)
16	**1k**	Me	1	99	65 (*R*)
17[d]	**1k**	Me	84	24	76 (*R*)
18[d]	**1k**	*t*-Bu	84	19	84 (*R*)

[a] All reactions were carried out in CH_2Cl_2 with 3 equiv of malonate ester, 3 equiv of BSA and 0.1 equiv of KOAc in the presence of 1.5 mol% of [(η^3-allyl)PdCl]$_2$ and 4 mol% of ligand **1** at r.t., unless otherwise noted.
[b] Isolated yield.
[c] Determined by chiral HPLC analysis (DAICEL CHIRALPAK AD, hexane/propan-2-ol, 95:5).
[d] The reaction was carried out at –40 °C.

Conclusion

In summary, novel P-chirogenic phosphine/sulfide hybrid ligands were prepared according to the phosphine-borane procedure. The Pd complexs of these P/S-hybrid ligands exhibited high catalytic activity and enantioselectivity in asymmetric allylic alkylation of 1-acetoxy-1,3-diphenyl-prop-2-ene with malonate esters.

All manipulations were carried out under Argon. NMR spectra were recorded on a Jeol JMN-LA400 spectrometer (396 MHz for ^{1}H and 100 MHz for ^{13}C), or Jeol JMN-LA500 spectrometer (500 MHz for ^{1}H, 126 MHz for ^{13}C and 202 MHz for ^{31}P). Chemical shifts are reported in δ (ppm) referenced to an internal tetramethylsilane standard for ^{1}H NMR and to an external 85% H_3PO_4 standard for ^{31}P NMR. Residual $CHCl_3$ (δ = 77.0 for ^{13}C) was used as internal reference for ^{13}C NMR. ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded in $CDCl_3$ at 25 °C unless otherwise noted. HPLC analysis was performed on a Shimadzu LC10AD liquid chromatograph system with chiral stationary phase column DAICEL CHIRALPAK AD. Compounds **2a** and **2b** were prepared according to the reported procedure described in the literature.[7,9]

(*R*)-Methylphenyl(*p*-toluenesulfonyloxymethyl)phosphine–borane (2c)

To a stirred, cooled (0 °C) solution of (*R*)-methylphenyl(hydroxymethyl)phosphine–borane (2.52 g, 15 mmol, 81% ee) in diisopropylethylamine (25 mL) was added *p*-toluenesulfonyl chloride (5.72 g, 30 mmol) and the mixture was vigorously stirred at r.t. After 1 h, the mixture was diluted with EtOAc and treated with 1 M HCl. The organic layer was separated and the aqueous layer was extracted with EtOAc (3 × 30 mL). The combined organic layers were washed with aq sat. $NaHCO_3$ solution and brine and dried (Na_2SO_4). The solvent was removed under reduced pressure and the residue was purified by flash chromatography on silica gel (hexane–EtOAc, 5:1) to give **2c** as a white solid; yield: 3.62 g (75%); mp 58.5–61.0 °C; $[\alpha]_D^{28}$ +6.8 (*c* = 0.51, $CHCl_3$).

IR (KBr): 2380, 1360, 1160, 1060, 985 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.65 (br q, J_{HB} = 96.0 Hz, 3 H, BH_3), 1.69 (d, $^2J_{HP}$ = 10.4 Hz, 3 H, CH_3), 2.44 (s, 3 H, ArC*H*$_3$), 4.26 (dd, *J* = 12.8 Hz, $^2J_{HP}$ = 2.5 Hz, 1 H, PCH_2O), 4.36 (d, *J* = 12.8 Hz, 1 H, PCH_2O), 7.29 (d, ^2J = 8.5 Hz, 2 H_{arom}), 7.44–7.48 (m, 2 H, C_6H_5), 7.53–7.57 (m, 1 H, C_6H_5), 7.64–7.66 (m, 2 H_{arom}), 7.69–7.73 (m, 2 H, C_6H_5).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 7.1 (d, J_{CP} = 39.3 Hz), 21.7, 65.8 (d, J_{CP} = 33.1 Hz), 125.6 (d, J_{CP} = 54.8 Hz), 128.1, 129.0 (d, $^2J_{CP}$ = 10.3 Hz), 130.1, 131.5, 132.1, 132.2 (d, $^3J_{CP}$ = 2.1 Hz), 145.6.

^{31}P NMR (202 Hz, $CDCl_3$): δ = 11.3–11.7 (m).

MS-FAB: *m*/*z* (%) = 321 (M^+ – H, 30), 137 (M^+ – CH_2OTs, 100).

HRMS: *m*/*z* Calcd for $C_{15}H_{19}BO_3PS$: 321.0886. Found 321.0889.

Anal. Calcd for $C_{15}H_{20}BO_3PS$: C 55.92, H 6.26. Found C 55.90, H 6.31.

Phosphine–Borane/Sulfides 3a–j; General Procedure

To a stirred suspension of NaH (60% oil suspension; 96 mg, 2.4 mmol) in DMF (5 mL) was added the appropriate thiol (2.4 mmol) at r.t. and the mixture was stirred for 0.5 h. The mixture was added to a solution of **2a–c** (2.0 mmol) in DMF (5 mL) at r.t. After 3 h, the mixture was quenched by 1 M HCl (30 mL) and extracted with Et_2O (3 × 30 mL). The organic layer was washed with aq sat. $NaHCO_3$ solution (20 mL) and brine (20 mL) and dried (Na_2SO_4). After evaporation of the solvent, the residue was chromatographed on silica gel (hexane–EtOAc, 10:1).

(*R*)-*tert*-Butylmethyl(*tert*-butylthiomethyl)phosphine–borane (3a)

Yield: 98%; colorless needles; mp 55–56 °C (hexane); $[\alpha]_D^{30}$ -36.9 (*c* = 0.52, $CHCl_3$).

IR (KBr): 2970, 2390, 1370, 1070, 910 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.48 (br q, J_{HB} = 91.9 Hz, 3 H, BH_3), 1.21 [d, $^3J_{HP}$ = 13.7 Hz, 9 H, $PC(CH_3)_3$], 1.32 (d, $^2J_{HP}$ = 9.4 Hz, 3 H, CH_3), 1.33 [s, 9 H, $SC(CH_3)_3$], 2.67 (dd, *J* = 13.2 Hz, $^2J_{HP}$ = 8.0 Hz, 1 H, PCH_2S), 2.78 (dd, *J* = 13.2 Hz, $^2J_{HP}$ = 8.9 Hz, 1 H, PCH_2S).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.6 (d, J_{CP} = 35.1 Hz), 20.3 (d, J_{CP} = 27.9 Hz), 25.6 (d, $^2J_{CP}$ = 3.1 Hz), 28.3 (d, J_{CP} = 32.0 Hz), 30.2, 44.3 (d, $^3J_{CP}$ = 3.1 Hz).

^{31}P NMR (202 Hz, $CDCl_3$): δ = 28.6 (J_{PB} = 52.0 Hz).

HRMS: *m*/*z* Calcd for $C_{10}H_{25}BPS$: 219.1508. Found 219.1510.

Anal. Calcd for $C_{10}H_{26}BPS$: C 54.55, H 11.90; Found: C 54.58, H 11.89.

(*R*)-Methylphenyl(*tert*-butylthiomethyl)phosphine–borane (3b)

Yield: 85%; colorless needles; mp 112–114 °C (hexane); $[\alpha]_D^{30}$ −26.7 (*c* = 0.56, $CHCl_3$).

IR (KBr): 2395, 1435, 1365, 1060, 910 cm^{-1}.

^{1}H NMR (396 MHz, $CDCl_3$): δ = 0.57 (br q, J_{HB} = 92.8 Hz, 3 H, BH_3), 1.25 [s, 9 H, $C(CH_3)_3$], 1.68 (d, $^2J_{HP}$ = 9.9 Hz, 3 H, CH_3), 2.86 (dd, *J* = 13.4 Hz, $^2J_{HP}$ = 7.6 Hz, 1 H, PCH_2S), 2.90 (dd, *J* = 13.4 Hz, $^2J_{HP}$ = 8.1 Hz, 1 H, PCH_2S), 7.44–7.54 (m, 3 H, C_6H_5-$H_{o,p}$), 7.74–7.79 (m, 2 H, C_6H_5-H_m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 8.8 (d, J_{CP} = 40.4 Hz), 25.9 (d, J_{CP} = 31.0 Hz), 30.2, 43.3 (d, $^3J_{CP}$ = 4.2 Hz), 128.6 (d, J_{CP} = 54.8 Hz), 128.6 (d, $^2J_{CP}$ = 10.3 Hz), 131.5 (d, $^4J_{CP}$ = 3.1 Hz), 131.7 (d, $^3J_{CP}$ = 9.3 Hz).

^{31}P NMR (202 Hz, $CDCl_3$): δ = 11.0 (J_{PB} = 53.4 Hz).

MS-FAB: *m*/*z* = 239 (M^+ – H, 100%).

HRMS: *m*/*z* Calcd for $C_{12}H_{22}BNaPS$: 263.1171. Found 263.1192.

Anal. Calcd for $C_{12}H_{22}BPS$: C 60.02, H 9.23. Found C 59.83, H 9.20.

(*R*)-*tert*-Butylmethyl(phenylthiomethyl)phosphine–borane (3c)

Yield: 97%; colorless cubes; mp 55.5–56.5 °C (hexane–EtOAc); $[\alpha]_D^{26}$ –43.1 (*c* = 1.38, $CHCl_3$).

IR (KBr): 2970, 2370, 1580, 1070, 740 cm^{-1}.

^{1}H NMR (396 MHz, $CDCl_3$): δ = 0.51 (br q, J_{HB} = 92.1 Hz, 3 H, BH_3), 1.23 [d, $^3J_{HP}$ = 14.0 Hz, 9 H, $C(CH_3)_3$], 1.35 (d, $^2J_{HP}$ = 9.7 Hz, 3 H, CH_3), 3.18 (d, $^2J_{HP}$ = 7.0 Hz, 2 H, PCH_2S), 7.21–7.25 (m, 1 H, C_6H_5-H_p), 7.29–7.33 (m, 2H, C_6H_5-H_m), 7.37–7.40 (m, 2 H, C_6H_5-H_o).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.7 (d, J_{CP} = 35.2 Hz), 25.4 (d, $^2J_{CP}$ = 3.1 Hz), 26.6 (d, J_{CP} = 24.8 Hz), 28.3 (d, J_{CP} = 31.0 Hz), 126.8, 129.2, 129.3, 136.4 (d, $^3J_{CP}$ = 4.1 Hz).

^{31}P NMR (202 Hz, $CDCl_3$): δ = 30.2 (J_{PB} = 55.5 Hz).

MS-FAB: *m*/*z* = 239 (M^+ – H, 100%).

HRMS: *m*/*z* Calcd for $C_{12}H_{22}BNaPS$: 263.1171. Found 263.1173.

Anal. Calcd for $C_{12}H_{22}BPS$: C 60.02, H 9.23. Found C 60.11, H 8.85.

(*S*)-*tert*-Butylmethyl(2-phenylthioethyl)phosphine–borane (3d)

Yield: 96%; colorless needles; mp 77–78 °C (hexane); $[\alpha]_D^{28}$ +13.3 (*c* = 0.49, $CHCl_3$).

IR (KBr): 2970, 2370, 1580, 1060, 740 cm^{-1}.

^{1}H NMR (396 MHz, $CDCl_3$): δ = 0.43 (br q, J_{HB} = 92.1 Hz, 3 H, BH_3), 1.12 [d, $^3J_{HP}$ = 13.7 Hz, 9 H, $C(CH_3)_3$], 1.22 (d, $^2J_{HP}$ = 9.7 Hz, 3 H, CH_3), 1.76–1.87 (m, 1 H, SCH_2), 1.91–2.01 (m, 1 H, SCH_2), 2.94–3.03 (m, 1 H, PCH_2), 3.21–3.31 (m, 1 H, PCH_2), 7.19–7.23 (m, 1 H, C_6H_5-H_p), 7.29–7.35 (m, 4 H, C_6H_5-$H_{o,m}$).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 5.5 (d, J_{CP} = 33.6 Hz), 21.6 (d, J_{CP} = 27.9 Hz), 25.0, 27.5 (d, J_{CP} = 33.6 Hz), 27.9, 126.5, 129.1, 129.4, 135.0.

^{31}P NMR (202 Hz, $CDCl_3$): δ = 26.2 (J_{PB} = 58.3 Hz).

MS-FAB: *m*/*z* = 253 (M^+ – H, 100%).

HRMS: *m*/*z* Calcd for $C_{13}H_{23}BPS$: 253.1351. Found 253.1354.

Anal. Calcd for $C_{13}H_{24}BPS$: C 61.43, H 9.52. Found: C 61.17, H 9.34.

(*R*)-*tert*-Butylmethyl[(2-methylphenylthio)methyl]phosphine–borane (3e):
Yield: 96%; colorless cubes; mp 48–50 °C (hexane); $[\alpha]_D^{30}$ –40.5 (*c* = 0.51, $CHCl_3$).

IR (KBr): 2360, 1590, 1470, 1060, 750 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.53 (br q, J_{HB} = 91.9 Hz, 3 H, BH_3), 1.24 [d, $^3J_{HP}$ = 14.0 Hz, 9 H, $C(CH_3)_3$], 1.37 (d, $^2J_{HP}$ = 9.8 Hz, 3 H, CH_3), 2.42 (s, 3 H, ArCH_3), 3.10 (dd, *J* = 13.4 Hz, $^2J_{HP}$ = 6.7 Hz, 1 H, PCH_2S), 3.13 (dd, *J* = 13.4 Hz, $^2J_{HP}$ = 8.4 Hz, 1 H, PCH_2S), 7.13–7.20 (m, 3 H_{arom}), 7.33–7.35 (m, 1 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.7 (d, J_{CP} = 35.2 Hz), 20.4, 25.5 (d, $^2J_{CP}$ = 2.1 Hz), 25.9 (d, J_{CP} = 24.8 Hz), 28.4 (d, J_{CP} = 32.1 Hz), 126.8, 126.9, 128.9, 130.4, 135.6 (d, $^3J_{CP}$ = 5.2 Hz), 138.1.

^{31}P NMR (202 Hz, $CDCl_3$): δ = 29.9 (J_{PB} = 54.3 Hz).

MS-FAB: *m*/*z* (%) = 277 (M + Na^+, 12), 251 (M^+ – 3 H, 84), 57 (*t*-Bu^+, 100).

HRMS: *m*/*z* Calcd for $C_{13}H_{24}BNaPS$: 277.1327. Found 277.1330.

Anal. Calcd for $C_{13}H_{24}BPS$: C 61.43, H 9.52. Found: C 61.30, H 9.49.

(*R*)-*tert*-Butylmethyl[(4-methylphenylthio)methyl]phosphine–borane (3f)
Yield: 89%; colorless needles; mp 49.5–50.5 °C (hexane–EtOAc); $[\alpha]_D^{30}$ –43.9 (*c* = 0.50, $CHCl_3$).

IR (KBr): 2390, 1490, 1070, 910, 810 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.50 (br q, J_{HB} = 92.6 Hz, 3 H, BH_3), 1.22 [d, $^3J_{HP}$ = 13.7 Hz, 9 H, $C(CH_3)_3$], 1.34 (d, $^2J_{HP}$ = 9.5 Hz, 3 H, CH_3), 2.33 (s, 3 H, ArCH_3), 3.13 (dd, *J* = 13.7 Hz, $^2J_{HP}$ = 6.0 Hz, 1 H, PCH_2S), 3.16 (dd, *J* = 13.7 Hz, $^2J_{HP}$ = 8.1 Hz, 1 H, PCH_2S), 7.12 (d, ^2J = 8.0 Hz, 2 H_{arom}), 7.29–7.32 (m, 2 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.7 (d, J_{CP} = 35.2 Hz), 21.0, 25.5 (d, $^2J_{CP}$ = 3.1 Hz), 27.4 (d, J_{CP} = 24.8 Hz), 28.3 (d, J_{CP} = 31.0 Hz), 130.0, 130.2, 132.8 (d, $^3J_{CP}$ = 4.1 Hz), 137.2.

^{31}P NMR (202 Hz, $CDCl_3$): δ = 30.1 (J_{PB} = 54.7 Hz).

MS-FAB: *m*/*z* (%) = 253 (M^+ – H, 100), 251 (M^+ – 3 H, 93), 57 (*t*-Bu^+, 93).

HRMS: *m*/*z* Calcd for $C_{13}H_{24}BNaPS$: 277.1327. Found 277.1354.

Anal. Calcd for $C_{13}H_{24}BPS$: C 61.43, H 9.52. Found C 61.19, H 9.38.

(*R*)-*tert*-Butylmethyl[(2-naphthylthio)methyl]phosphine–borane (3g)
Yield: 98%; colorless needles; mp 66–67 °C (hexane); $[\alpha]_D^{28}$ –51.8 (*c* = 0.49, $CHCl_3$).

IR (KBr): 2390, 1460, 1070, 920, 815 cm^{-1}.

^{1}H NMR (396 MHz, $CDCl_3$): δ = 0.56 (br q, J_{HB} = 89.8 Hz, 3 H, BH_3), 1.26 [d, $^3J_{HP}$ = 13.7 Hz, 9 H, $C(CH_3)_3$], 1.38 (d, $^2J_{HP}$ = 9.7 Hz, 3 H, CH_3), 3.28 (d, $^2J_{HP}$ = 7.3 Hz, 2 H, PCH_2S), 7.43–7.52 (m, 3 H_{arom}), 7.76–7.81 (m, 4 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.8 (d, J_{CP} = 35.1 Hz), 25.5 (d, $^2J_{CP}$ = 2.1 Hz), 26.4 (d, J_{CP} = 23.8 Hz), 28.4 (d, J_{CP} = 32.1 Hz), 126.1, 126.8, 127.0, 127.2, 127.3, 127.7, 128.8, 132.0, 133.7, 133.8 (d, $^3J_{CP}$ = 4.1 Hz).

^{31}P NMR (202 Hz, $CDCl_3$): δ = 30.4 (J_{PB} = 54.7 Hz).

MS-FAB: *m*/*z* (%) = 289 (M^+ – H, 46), 161 (M^+ – Np – 2 H, 100), 57 (*t*-Bu^+, 56).

HRMS: *m*/*z* Calcd for $C_{16}H_{23}BPS$: 289.1351. Found 289.1354.

Anal. Calcd for $C_{16}H_{24}BPS$: C 66.22, H 8.34. Found C 65.94, H 7.96.

(*R*)-*tert*-Butylmethyl[(4-nitrophenylthio)methyl]phosphine–borane (3h)
Yield: 26%; pale yellow needles; mp 128.5–129.5 °C (hexane–EtOAc); $[\alpha]_D^{28}$ –55.2 (*c* = 0.53, $CHCl_3$).

IR (KBr): 2380, 1580, 1510, 1340, 1070 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.55 (br q, J_{HB} = 93.0 Hz, 3 H, BH_3), 1.27 [d, $^3J_{HP}$ = 14.3 Hz, 9H, $C(CH_3)_3$], 1.39 (d, $^2J_{HP}$ = 9.8 Hz, 3 H, CH_3), 3.21 (dd, *J* = 13.1 Hz, $^2J_{HP}$ = 9.5 Hz, 1 H, PCH_2S), 3.27 (dd, *J* = 13.1 Hz, $^2J_{HP}$ = 5.8 Hz, 1 H, PCH_2S), 7.40–7.43 (m, 2 H_{arom}), 8.14–8.18 (m, 2 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 5.0 (d, J_{CP} = 34.1 Hz), 24.6 (d, J_{CP} = 23.8 Hz), 25.4 (d, $^2J_{CP}$ = 2.1 Hz), 28.5 (d, J_{CP} = 31.1 Hz), 124.2, 126.7, 145.8, 146.3 (d, $^3J_{CP}$ = 4.1 Hz).

^{31}P NMR (202 Hz, $CDCl_3$): δ = 31.1 (J_{PB} = 50.6 Hz).

MS-FAB: *m*/*z* (%) = 284 (M^+ – H, 35), 154 ($NO_2C_6H_4S^+$, 100), 136 (74).

HRMS: *m*/*z* Calcd for $C_{12}H_{20}BNO_2PS$: 284.1045. Found 284.1048.

Anal. Calcd for $C_{12}H_{21}BNO_2PS$: C 50.54, H 7.42, N 4.91. Found: C 50.41, H 7.39, N 4.90.

(*R*)-*tert*-Butylmethyl(cyclohexylthiomethyl)phosphine–borane (3i, Cy = cyclohexyl)
Yield: 92%; colorless needles; mp 40–41 °C (hexane); $[\alpha]_D^{28}$ –67.8 (*c* = 0.53, $CHCl_3$).

IR (KBr): 2930, 2380, 1450, 1060, 915 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.46 (br q, J_{HB} = 88.2 Hz, 3 H, BH_3), 1.20 [d, $^3J_{HP}$ = 13.7 Hz, 9 H, $C(CH_3)_3$], 1.32 (d, $^2J_{HP}$ = 9.7 Hz, 3 H, CH_3), 1.27–1.36 (m, 5 H, CyH), 1.59–1.65 (m, 1 H, CyH), 1.73–1.82 (m, 2 H, CyH), 1.94–2.04 (m, 2 H, CyH), 2.71 (dd, *J* = 13.7 Hz, $^2J_{HP}$ = 5.8 Hz, 1 H, PCH_2S), 2.77 (dd, *J* = 13.7 Hz, $^2J_{HP}$ = 8.8 Hz, 1 H, PCH_2S), 2.73–2.79 (m, 1 H, CyH).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.6 (d, J_{CP} = 36.2 Hz), 21.8 (d, J_{CP} = 26.9 Hz), 25.5 (d, $^2J_{CP}$ = 2.1 Hz), 25.7, 25.9, 26.0, 28.2 (d, J_{CP} = 31.0 Hz), 33.0, 33.1, 46.1 (d, $^3J_{CP}$ = 3.1 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 29.1 (J_{PB} = 57.0 Hz).

MS-FAB: *m*/*z* = 245 (M^+ – H, 100%).

HRMS: *m*/*z* Calcd for $C_{12}H_{27}BPS$: 245.1664. Found 245.1667.

Anal. Calcd for $C_{12}H_{28}BPS$: C 58.54, H 11.46. Found C 58.15, H 11.45.

(*R*)-*tert*-Butylmethyl[(phenylmethylthio)methyl]phosphine–borane (3j)
Yield:93%; colorless needles; mp 48–50 °C (hexane); $[\alpha]_D^{26}$ –155.2 (*c* = 0.50, $CHCl_3$).

IR (KBr): 2970, 2370, 1070, 910, 700 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.52 (br q, J_{HB} = 91.7 Hz, 3 H, BH_3), 1.13 [d, $^3J_{HP}$ = 13.4 Hz, 9 H, $C(CH_3)_3$], 1.24 (d, $^2J_{HP}$ = 9.4 Hz, 3 H, CH_3), 2.53 (dd, J = 14.0 Hz, $^2J_{HP}$ = 9.1 Hz, 1 H, PCH_2S), 2.57 (dd, J = 14.0 Hz, $^2J_{HP}$ = 4.6 Hz, 1 H, PCH_2S), 3.82 (d, J = 13.2 Hz, 1 H, CCH_2S), 3.89 (d, J = 13.2 Hz, 1 H, CCH_2S), 7.25–7.28 (m, 1 H, C_6H_5-H_p), 7.31–7.35 (m, 4 H, C_6H_5-$H_{o,m}$).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 4.7 (d, J_{CP} = 36.2 Hz), 22.1 (d, J_{CP} = 27.9 Hz), 25.3 (d, $^2J_{CP}$ = 2.0 Hz), 28.1 (d, J_{CP} = 31.1 Hz), 38.4 (d, $^3J_{CP}$ = 3.1 Hz), 127.4, 128.6, 129.2, 137.2.

^{31}P NMR (202 Hz, $CDCl_3$): δ = 29.8 (J_{PB} = 56.0 Hz).

MS-FAB: m/z = 253 (M^+ – H, 100%).

HRMS: m/z Calcd for $C_{13}H_{23}BPS$: 253.1351. Found 253.1354.

Anal. calcd for $C_{13}H_{24}BPS$: C 61.43, H 9.52. Found C 61.20, H 9.47.

(*R*)-*tert*-Butylmethyl(phenylthiomethyl)phosphine–borane (3c) from 4a

To a stirred, cooled (–78 °C) solution of (–)-sparteine (1.41 g, 6 mmol) in Et_2O (10 mL) was added *s*-BuLi (5.5 mL of a 1.0 M cyclohexane–hexane solution, 5.5 mmol). After 15 min, a solution of **4a** (660 mg, 5 mmol) in Et_2O (10 mL) was added dropwise and the mixture was stirred at –78 °C. After 3 h, the solution was added to a Et_2O solution (20 mL) of diphenyl disulfide (1.64 g, 7.5 mmol) via cannula at 0 °C and the mixture was allowed to warm to r.t. After 2 h, the reaction was quenched by the addition of 1 M HCl and the organic layer was separated. The aqueous phase was extracted with EtOAc (3 × 30 mL) and the combined organic layers were washed with aq sat. $NaHCO_3$ solution and brine and dried (Na_2SO_4). The solvent was removed under reduced pressure and the residue was purified by flash chromatography on silica gel (hexane–EtOAc 10:1) to give **3c** in 92% yield.

(*R*)-1-Adamantylmethyl(phenylthiomethyl)phosphine–borane (3k)

To a stirred, cooled (–78 °C) solution of (–)-sparteine (914 mg, 3.9 mmol) in Et_2O (60 mL) was added *s*-BuLi (3.6 mL of a 1.0 M cyclohexane–hexane solution, 3.6 mmol). After 15 min, a solution of **4b** (630 mg, 3.0 mmol) in toluene (20 mL) was added dropwise and the mixture was stirred at –78 °C. After 3 h, the solution was added to a Et_2O solution (30 mL) of diphenyl disulfide (982 mg, 4.5 mmol) via cannula at 0 °C and the mixture was allowed to warm to r.t. After 2 h, the reaction was quenched by the addition of 1 M HCl and the organic layer was separated. The aqueous phase was extracted with EtOAc (3 × 20 mL) and the combined organic layer was washed with aq sat. $NaHCO_3$ solution and brine and dried (Na_2SO_4). The solvent was removed under reduced pressure and the residue was purified by flash chromatography on silica gel (hexane–EtOAc, 10:1) to give **3k**; yield: 69%; colorless needles; mp 96.5–98.0 °C (hexane–Et_2O); $[\alpha]_D^{28}$ –53.5 (c = 0.50, $CHCl_3$).

IR (KBr): 2910, 2850, 2370, 1060, 745 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.47 (br q, J_{HB} = 91.1 Hz, 3 H, BH_3), 1.31 (d, $^2J_{HP}$ = 9.4 Hz, 3 H), 1.71–1.80 (m, 6 H), 1.87–1.89 (m, 6 H), 2.05 (br, 3 H), 3.12 (dd, J = 13.5 Hz, $^2J_{HP}$ = 5.7 Hz, 1 H, PCH_2S), 3.20 (dd, J = 13.5 Hz, $^2J_{HP}$ = 8.7 Hz, 1 H, PCH_2S), 7.20–7.24 (m, 1 H, C_6H_5-H_p), 7.29–7.33 (m, 2 H, C_6H_5-H_m), 7.36–7.39 (m, 2 H, C_6H_5-H_o).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 3.2 (d, J_{CP} = 36.2 Hz), 25.4 (d, J_{CP} = 24.8 Hz), 27.6 (d, $^2J_{CP}$ = 8.2 Hz), 31.2 (d, J_{CP} = 32.1 Hz), 36.2, 36.4, 126.7, 129.1, 129.2, 136.6 (d, $^3J_{CP}$ = 4.1 Hz).

^{31}P NMR (202 Hz, $CDCl_3$): δ = 25.5–26.2 (m).

MS-FAB: m/z (%) = 315 (M^+ – H, 76), 135 (adamantyl$^+$ – H, 100).

HRMS: m/z Calcd for $C_{18}H_{27}BPS$: 317.1664. Found 317.1668.

Anal. Calcd for $C_{18}H_{28}BPS$: C 67.93, H 8.87. Found: C 67.84, H 9.01.

P-Chirogenic Phosphine/Sulfide Hybrid Ligands 1a,c–k; General Procedure

To a stirred, cooled (0 °C) solution of **3a**,**c**–**k** (0.5 mmol) in degassed toluene (4 mL) was slowly added trifluoromethanesulfonic acid (130 μL, 1.5 mmol) and the mixture was stirred for 30 min in an ice-bath. The mixture was further stirred at r.t. for 1 h and concentrated under reduced pressure. A solution of KOH (140 mg, 2.5 mmol) in degassed EtOH–H_2O (1.5 mL, 10:1) was slowly added to the resulting pasty oil and the mixture was stirred at 50 °C for 1-2 h and cooled to r.t. The mixture was diluted with Et_2O (3 mL) and allowed to stand. The supernatant was separated and the suspended aqueous layer was extracted with freshly distilled Et_2O (2 × 3 mL) and the combined Et_2O phases were dried (Na_2SO_4) under argon. The solution was filtered through basic alumina column under argon and concentrated under reduced pressure to give practically pure **1a**,**c**–**k** as colorless oil.

(*R*)-*tert*-Methylphenyl(*tert*-butylthiomethyl)phosphine (1b)

The phosphine–borane **3b** (24.0 mg, 0.1 mmol) was dissolved in 1-methylpyrrolidine (2 mL) and the solution was stirred for 3 h at 50 °C. The volatile was removed as the toluene azeotrope (3 × 1 mL) under reduced pressure (ca. 0.1 Torr) and the residue was filtered through silica gel column with toluene elution under argon. The filtrate was evaporated in vacuo to give **1b** as colorless oil.

Allylic Alkylation of 1-Acetoxy-1,3-diphenylprop-2-ene with Malonate Esters Catalyzed by Pd Complexes of 1; General Procedure

To a CH_2Cl_2 (5 mL) solution of **1a**–**k** (0.04 mmol) was added di(μ-chloro)bis(η^3-allyl)dipalladium(II) (5.5 mg, 0.015 mmol) at r.t. and the solution was stirred for 1 h at this temperature. To the solution were added a solution of 1-acetoxy-1,3-diphenylprop-2-ene (252 mg, 1.0 mmol) in CH_2Cl_2 (0.5 mL), *N*,*O*-bis(trimethylsilyl)acetamide (743 μL, 3.0 mmol), KOAc (9.8 mg, 0.1 mmol) and malonate ester (3 mmol) at –78 °C and the mixture was stirred at r.t. or –40 °C. The reaction was quenched by aq sat. NH_4Cl solution and diluted with Et_2O and the organic layer was separated from the aqueous layer. The Et_2O phase was washed with aq sat. NH_4Cl and aq sat. $NaHCO_3$ solutions followed by brine and dried (Na_2SO_4). The solution was concentrated under reduced pressure and the residue was chromatographed on silica gel (hexane–EtOAc, 5:1). The enantiomeric excess of the allylation products was determined by HPLC analysis using a chiral stationary column (DAICEL CHIRALPAK AD; hexane–propan-2-ol, 95:5).

Acknowledgement

This work was supported by a Grant-in Aid for Scientific Research on Priority Area “Exploitation of Multi-element Cyclic Molecules” No. 12139299 from the Ministry of Education, Science, Sports and Culture, Japan.

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