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Synthesis of Enantiopure P-Stereogenic Diphosphacrowns using P-Stereogenic Secondary Phosphines

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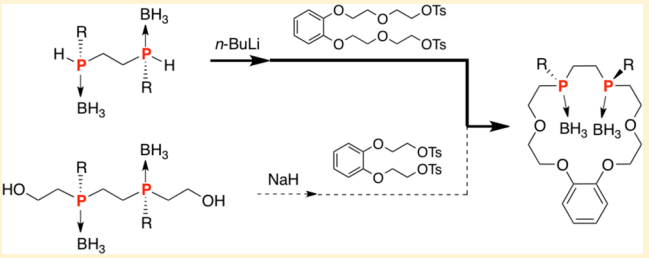
Supporting Information

ABSTRACT: A new synthetic route to enantiopure P-stereogenic benzodiphosphacrowns using a P-stereogenic secondary bisphosphine as the key building block is reported. Syntheses of the enantiomer and P-stereogenic crowns with various ring structures, as well as deboranation of the crown compounds and subsequent reaction with a platinum complex, are described.



Phosphine (PR_3) is a three-coordinated organophosphorus compound with an unshared electron pair and three covalent bonds. The structure of a phosphine is very similar to that of a tertiary amine (NR_3); however, the *p* character of the sp^3-hybridized orbital of the three bonds and the *s*-character of the sp^3-hybridized orbital of the unshared electron pair of PR_3 are higher than those of NR_3. As a result, the inversion energy of PR_3 is higher than that of NR_3.[1] Thus, the phosphorus atom can act as a chiral center, and an enantiopure P-stereogenic phosphine normally exists as a structurally stable compound at room temperature. From this structural viewpoint, a variety of P-stereogenic phosphines have been prepared;[2] in particular, P-stereogenic bisphosphines have been widely employed as chiral chelate ligands for transition metal-catalyzed asymmetric hydrogenations.[3,4]

Our recent efforts were directed toward the syntheses of various cyclic phosphines such as *trans*-1,4-diphosphacyclohexanes,[5] 12-phosphacrown-4,[6] and enantiopure diphosphacrowns[7] from P-stereogenic bisphosphine BisP*–borane complexes, which were developed by Evans[8] and Imamoto,[9] as building blocks. Among these cyclic phosphines, enantiopure diphosphacrowns have a unique structure consisting of two P-stereogenic centers in the crown ether ring. However, until recently, there have been no reports on the synthesis of enantiopure crown ether derivatives containing chiral heteroatoms that interact directly with guests in the ring skeleton,[10,11] although a notable number of optically active crown ether derivatives have been prepared since the discovery of dibenzo-18-crown-6 in 1967.[12] The poor isolated yields (~20%) of the enantiopure diphosphacrowns obtained by our synthesis approach[7] would severely restrict the widespread application of these compounds as chiral ligands, NMR chiral shift reagents, optical resolution reagents, etc. Herein, we report a new synthetic route that affords enantiopure diphosphacrowns in much better isolated yields than does the previous method.

Scheme 1 describes the synthetic route to the target (*R*,*R*)-benzodiphosphacrowns (*R*,*R*)-**5a–c** from P-stereogenic phosphine borane complex (*R*)-**1**. The synthesis of (*R*)-**1**,[13,14] (*S*,*S*)-**2**,[15] and (*S*,*S*)-**3**[15] has already established by Imamoto and co-workers; in this scheme, our results are shown. The reaction of enantiomerically enriched (*R*)-**1** with *s*-BuLi and *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA) afforded a lithiated species, which was subjected to oxidative coupling by the treatment with $CuCl_2$ and aqueous NH_3 to obtain the corresponding P-stereogenic bisphosphine (*S*,*S*)-**2** in 52% isolated yield. Notably, selective oxidative coupling of the carbon–carbon bond proceeded without carbon–oxygen or oxygen–oxygen bond formation.[15] Successive Ru-catalyzed oxidation in the presence of $K_2S_2O_8$/KOH and decarboxylation converted the hydroxymethyl group of (*S*,*S*)-**2** into hydrogen to afford secondary bisphosphine borane complex (*S*,*S*)-**3** in 82% isolated yield. Deprotonation of (*S*,*S*)-**3** by *n*-BuLi and the subsequent reaction with electrophiles **4a–c** afforded (*R*,*R*)-benzodiphosphacrowns (*R*,*R*)-**5a–c** in 28–62% isolated yields.

We investigated the substrate scope of this synthetic strategy and confirmed that the corresponding (*R*,*R*)-naphtho-18-diphosphacrown-6 (*R*,*R*)-**5d** and (*R*,*R*)-18-diphosphacrown-6 (*R*,*R*)-**5e** skeletons (Chart 1) could be constructed by the same procedure.

The enantiomer (*S*,*S*)-benzo-18-diphosphacrown-6 borane complex (*S*,*S*)-**5b** was synthesized as shown in Scheme 2.[16] Reaction of P-stereogenic bisphosphine borane complex (*S*,*S*)-**6**, which was also prepared by Imamoto and co-workers,[9,17] with *s*-BuLi/TMEDA led to the formation of a dilithiated intermediate. Acid treatment after bubbling oxygen through the reaction mixture afforded the corresponding dialcohol (*R*,*R*)-**2** in 36% isolated yield. Oxidation and decarboxylation of the hydroxymethyl group gave (*R*,*R*)-**3** in 81% isolated yield.

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Scheme 1

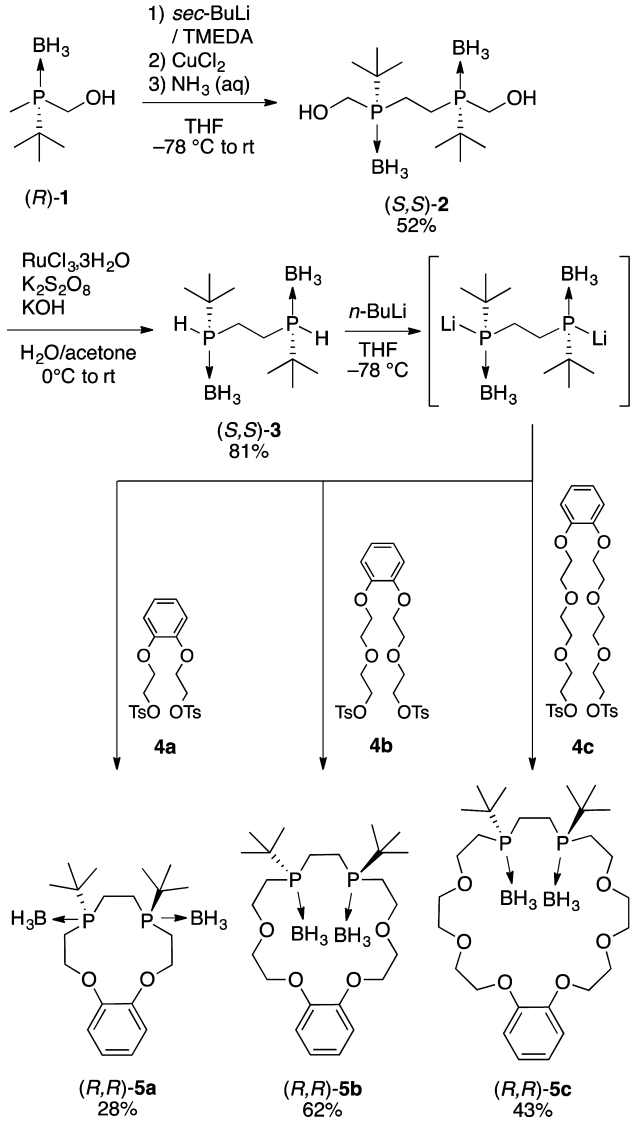
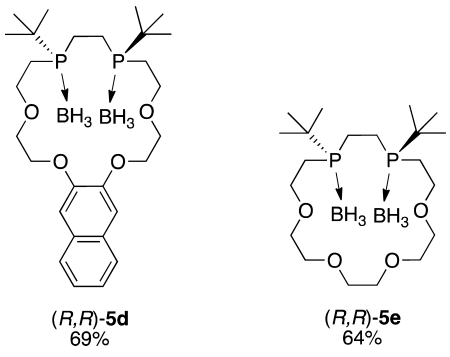


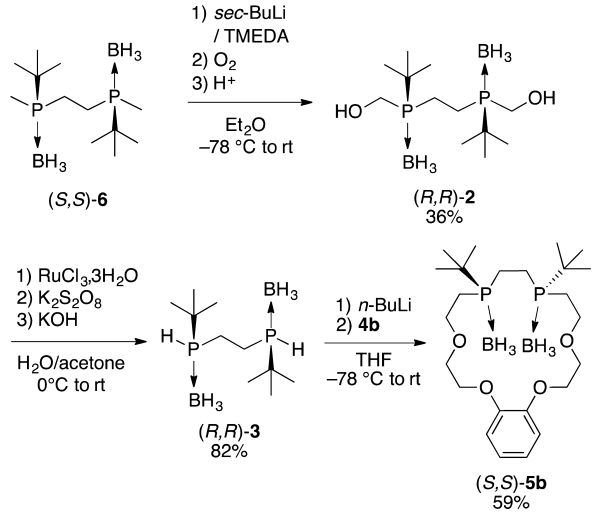
Chart 1



Finally, (*R*,*R*)-**3** was reacted with *n*-BuLi and **4b** to obtain the desired enantiomer (*S*,*S*)-**5b** in 59% isolated yield.

The structures of all diphosphacrowns (*R*,*R*)-**5a**–**e** and (*S*,*S*)-**5b** were confirmed by ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy, high-resolution mass analysis, and elemental analysis. Liquid chromatography analysis using chiral columns revealed that (*R*,*R*)-**5b** and (*S*,*S*)-**5b** were obtained in almost 100% enantiomeric excess (ee), as shown in Figure S16 (Supporting Information), in comparison with the corresponding racemic compound (*rac*)-**5b** prepared from (*rac*)-**1**.[18] Single crystals of (*R*,*R*)-**5a**–**c** suitable for X-ray crystallography were obtained by recrystallization from CH_2Cl_2 and hexane. Figure 1 and Table 1 show the molecular structures and crystal data of (*R*,*R*)-**5a**–**c**, respectively. The benzodiphosphacrowns consist of two P-stereogenic centers, with the absolute configuration being *R*. As in the case of common P-stereogenic bisphosphines, two *tert*-butyl groups on the chiral phosphorus atoms are located at two diagonal quadrants. The ring sizes of the benzodiphosphacrowns are slightly larger than those of the corresponding crowns because P–C bonds (average length: approximately 1.832 Å) are longer than O–C bonds (average length: approximately 1.413 Å).

Scheme 2



The coordinated boranes of the benzodiphosphacrowns could be readily removed by reaction with an organic base such as morpholine to quantitatively afford the corresponding free phosphines as air-sensitive colorless solids; the deboronation of (*R*,*R*)-**5b** and the relevant ^{31}P NMR spectra are shown in Figure S20 (Supporting Information). Subsequent reaction of (*R*,*R*)-**5b**′ with $PtCl_2$(cod) (cod = 1,5-cyclooctadiene) gave the corresponding $PtCl_2$[(*R*,*R*)-benzo-18-diphosphacrown-6] complex in 37% isolated yield, as shown in Figure S20 (Supporting Information). The structure of the complex was confirmed by NMR spectroscopy, mass analysis, elemental analysis, and X-ray crystallography. In the ^{31}P NMR spectrum, a typical satellite signal derived from P–Pt coupling (J_{P-Pt} = 3609 Hz) was observed together with the signal at δ +55.3 ppm. According to the X-ray structure, Pt was located outside the diphosphacrown ring (Figure S24, Supporting Information). The front view of the complex showed the clear optically active "8-shaped" structure of the crown ring, indicating the existence of topological chirality due to complexation with the transition metal, in addition to the local chirality around the P-stereogenic centers. Two *tert*-butyl groups were located at the two diagonal quadrants and occupied quasi-equatorial positions (Figure S24, Supporting Information). Therefore, benzodiphosphacrowns can be employed as the chiral ligands for various transition-metal-catalyzed asymmetric reactions.[7b]

In conclusion, we developed a new synthetic route to enantiopure P-stereogenic crown ethers. P-Stereogenic secondary phosphines could be easily lithiated by *n*-BuLi and subsequently reacted with various tosylated crown ether

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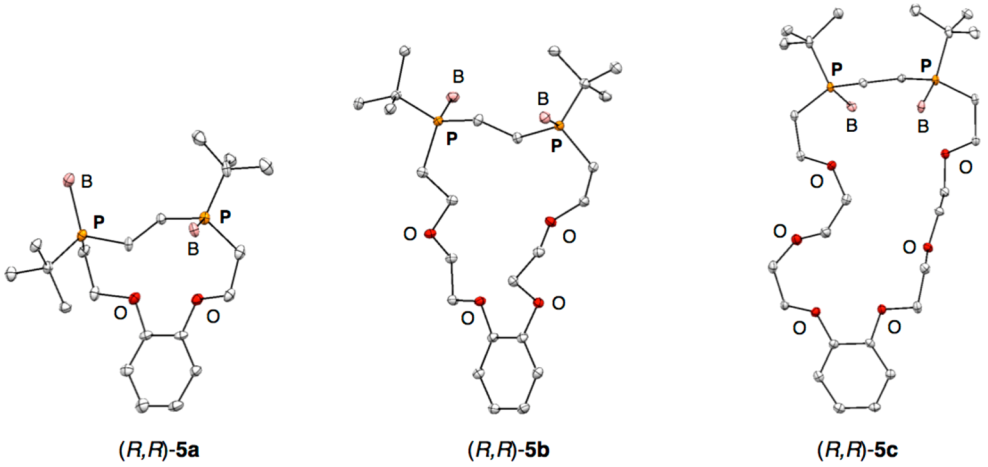

Figure 1. ORTEP drawings of (*R,R*)-**5a−c**. Thermal ellipsoids are drawn at the 30% probability level. Hydrogen atoms are omitted for clarity.

Table 1. Crystallographic Data for (*R,R*)-5a−c

	(*R,R*)-**5a**	(*R,R*)-**5b**	(*R,R*)-**5c**
formula	$C_{20}H_{40}B_2O_2P_2$	$C_{24}H_{48}B_2O_4P_2$	$C_{28}H_{56}B_2O_6P_2$
formula weight	396.08	484.18	572.29
crystal dimensions (mm)	0.40 × 0.20 × 0.20	0.30 × 0.20 × 0.20	0.30 × 0.30 × 0.20
T (K)	100(2)	103(2)	99(2)
crystal system	orthorhombic	orthorhombic	orthorhombic
space group	$P2_12_12_1$	$P2_12_12_1$	$P2_12_12_1$
unit cell dimensions			
a (Å)	10.8850(5)	6.6655(2)	10.5555(6)
b (Å)	11.4534(5)	13.8497(4)	16.2892(9)
c (Å)	18.6129(9)	30.6661(10)	19.6227(10)
V (Å^3)	2320.48(18)	2830.95(15)	3373.9(3)
Z	4	4	4
d_{calc} (g cm^{-3})	1.134	1.136	1.127
absorption coeff	0.199	0.179	0.164
F(000)	864	1056	1248
θ range for data collection (deg)	3.39−27.46	3.02−27.48	3.10−27.45
index ranges	$-13 \le h \le 13$	$-8 \le h \le 8$	$-13 \le h \le 13$
	$-14 \le k \le 13$	$-17 \le k \le 17$	$-21 \le k \le 21$
	$-24 \le l \le 24$	$-39 \le l \le 39$	$-25 \le l \le 25$
reflections measured/independent	21677/5274	42385/6474	31247/7686
goodness-of-fit on F^2	1.188	1.132	1.123
R [$I > 2\sigma(I)$]	R_1 = 0.0541	R_1 = 0.0448	R_1 = 0.0412
	wR_2 = 0.1191	wR_2 = 0.0940	wR_2 = 0.0864
Flack parameter	0.01(15)	0.00(9)	0.01(8)

precursors to afford the target P-stereogenic (*R,R*)-benzodiphosphacrowns and the enantiomer (*S,S*)-benzo-18-diphosphacrown-6 in moderate-to-good isolated yields, regardless of the ring size. P-Stereogenic crowns with other ring structures, (*R,R*)-naphtho-18-diphosphacrown-6 and (*R,R*)-18-diphosphacrown-6, could also be prepared by the same procedure. The straightforward deboranation and transition metal complexation of these phosphines would allow for their use as chiral ligands for transition-metal-catalyzed asymmetric reactions. Further studies on the complexation behaviors of this class of enantiopure diphosphacrowns with various transition metals as well as main-group metals are underway.

EXPERIMENTAL SECTION

General Experimental Details. ^{1}H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded on a 400 MHz spectrometer, and samples were analyzed in $CDCl_3$ using Me_4Si as an internal standard. ^{31}P (161.9 MHz) NMR spectra were also recorded on a 400 MHz spectrometer, and samples were analyzed in $CDCl_3$ using H_3PO_4 as an external standard. The following abbreviations are used: s, singlet; d, doublet; t, triplet; m, multiplet; q, quartet; br, broad. High-resolution mass spectra (HRMS) were obtained by a fast atom bombardment (FAB) using a double-focusing mass spectrometer or electron spray ionization (ESI) technique using an orbitrap mass spectrometer. Optical rotation was measured using $CHCl_3$ as a solvent. Recyclable preparative high-performance liquid chromatography (HPLC) was performed using $CHCl_3$ as an eluent. Enantiomeric purity was confirmed by a HPLC with a chiral column (0.46 cm × 25 cm) using hexane/THF as an eluent. Analytical thin-layer chromatography was performed with SiO_2 plates. Column chromatography was performed with SiO_2.

THF, Et_2O, and Et_3N were purchased and purified by passage through purification column under Ar pressure.[19] Dehydrated grade solvents of CH_2Cl_2, DMF, and CH_3CN were purchased and used without further purification. *N,N,N′,N′*-Tetramethylethylenediamine (TMEDA) was purchased and distilled from KOH under Ar

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atmosphere. *s*-BuLi (1.0 M in cyclohexane and *n*-hexane solution), *n*-BuLi (1.6 M in cyclohexane and *n*-hexane solution), TsCl, NaOH, 2-(2-hydroxyethoxy)ethyl chloride, 2-[2-(2-hydroxyethoxy)ethoxy]ethyl chloride, catechol, 2,3-dihydroxynaphthalene, *O*,*O*′-bis(2-hydroxyethoxy)benzene, penta(ethylene glycol) bis(*p*-toluenesulfonate) **4e**, K_2CO_3, $RuCl_3{\cdot}nH_2O$, $K_2S_2O_8$, KOH, $CuCl_2$, and aqueous NH_3 (28%) were purchased and used without purification. Compounds (*R*)-**1**[13] and (*S*,*S*)-**6**[9] were prepared by the procedure of the literature. A modified previously published procedure was used for compounds (*S*,*S*)-**2** and (*S*,*S*)-**3**.[15]

Synthesis of (*S*,*S*)-2. A THF solution (100 mL) of (*R*)-**1** (1.48 g, 10.0 mmol) and TMEDA (3.58 mL, 24.0 mmol) was cooled to −78 °C under Ar atmosphere. *s*-BuLi (1.0 M in cyclohexane and *n*-hexane, 24.0 mL, 24.0 mmol) was added by a syringe. After the mixture was stirred for 3 h, $CuCl_2$ (4.04 g, 30 mmol) was added in one portion. After the mixture was stired for an additional 2 h at room temperature, 28% NH_3 aq (50 mL) was added. The organic layer was extracted with AcOEt (3 × 100 mL). The combined organic layers were washed with 5% NH_3 aq, 1 N HCl aq, and brine and then dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with AcOEt and hexane (v/v = 1/3) as an eluent, and recrystallization from toluene gave (*S*,*S*)-**2** (764.7 mg, 2.60 mmol, 52%) as a colorless solid. R_f = 0.35 (AcOEt and hexane, v/v = 1/1). Spectroscopic data were consistent with those reported in the literature.[3]

Synthesis of (*S*,*S*)-3. An aqueous solution (30 mL) of KOH (2.24 g, 40 mmol) and $K_2S_2O_8$ (3.24 g, 12 mmol) was cooled to 0 °C. After addition of $RuCl_3{\cdot}nH_2O$ (104.6 mg, 0.40 mmol) to the aqueous solution, an acetone solution (20 mL) of (*S*,*S*)-**2** (588.0 mg, 2.0 mmol) was added dropwise. The reaction mixture was allowed to warm to room temperature. After being stirred for 4 h, the reaction was quenched by addition of 2 N HCl aq (50 mL). The organic layer was extracted with Et_2O (3 × 100 mL). The combined organic layers were washed with brine and dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with AcOEt and hexane (v/v = 1/2) as an eluent, and recrystallization from toluene and hexane gave (*S*,*S*)-**3** (380.1 mg, 1.63 mmol, 81%) as a colorless solid. R_f = 0.75 (AcOEt and hexane, v/v = 1/1). Spectroscopic data were consistent with those reported in the literature.[4]

Synthesis of 4a. *O*,*O*′-Bis(2-hydroxyethoxy)benzene (1.00 g, 5.04 mmol) was dissolved in Et_3N (4.5 mL) and CH_2Cl_2 (13.0 mL), and the solution was cooled to 0 °C. To this solution was added TsCl (2.88 g, 15.1 mmol) in one portion. After 10 min, the reaction was allowed to warm to room temperature. After being stirred for 1 day, the solution was washed with water (2 × 20 mL), saturated $NaHCO_3$ aq (20 mL), and saturated citric acid aq (20 mL) and then dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was purified by column chromatography on SiO_2 with AcOEt and hexane (v/v = 1/3) as an eluent, and recrystallization from $CHCl_3$ and MeOH gave **4a** (2.06 g, 4.07 mmol, 81%) as a colorless solid. R_f = 0.50 (AcOEt and hexane, v/v = 1/1). Spectroscopic data was consistent with those reported in the literature.[20]

Synthesis of 4b. Catechol (3.30 g, 30.0 mmol) and K_2CO_3 (12.4 g, 90.0 mmol) were added to dry DMF (35 mL). The resulting suspension was stirred vigorously, and 2-(2-hydroxyethoxy)ethyl chloride (11.2 g, 90.0 mmol) was added dropwise to the reaction mixture. The mixture was heated under reflux for 1 day. After being cooled to room temperature, the mixture was filtered to remove K_2CO_3 and concentrated under reduced pressure. The residue was poured into H_2O (30 mL) and extracted with $CHCl_3$ (4 × 50 mL). The combined organic layers were dried over Na_2SO_4. After filtration, the solvent was removed in vacuo to yield crude compound 1,2-bis[2-(2-hydroxyethoxy)ethoxy]benzene.

Without further purification, 4.4 M NaOH aq (25 mL) was added to the solution of 1,2-bis[2-(2-hydroxyethoxy)ethoxy]benzene in THF (25 mL). The stirred solution was cooled to 0 °C, and a solution of TsCl (13.3 g, 70.0 mmol) in THF (35 mL) was added dropwise over 20 min. Stirring was continued for an additional day at room temperature, and then 2 N HCl (100 mL) was added. The mixture was extracted with toluene (2 × 100 mL). The organic layer was separated from the aqueous layer and washed with H_2O (2 × 50 mL), saturated $NaHCO_3$ aq (2 × 50 mL), and H_2O again (2 × 50 mL). The organic layer was dried over $MgSO_4$. After filtration, the solvent was evaporated in vacuo. The residue was purified by column chromatography on SiO_2 with CH_2Cl_2 and AcOEt (v/v = 80/1) as an eluent. The solvent was evaporated to obtain **4b** (13.0 g, 21.8 mmol, 73%) as a colorless oil. R_f = 0.10 (CH_2Cl_2 and AcOEt, v/v = 80/1). Spectroscopic data were consistent with those reported in the literature.[21]

Synthesis of 4c. Catechol (3.30 g, 30.0 mmol) and K_2CO_3 (12.4 g, 90.0 mmol) were added to dry CH_3CN (100 mL). The resulting suspension was stirred vigorously, and 2-[2-(2-hydroxyethoxy)-ethoxy]ethyl chloride (15.2 g, 90.0 mmol) was added dropwise to the reaction mixture. The mixture was heated under reflux for 2 days. The solution was filtered to remove K_2CO_3 and concentrated under reduced pressure. The residue was washed with CH_2Cl_2 (50 mL). The filtrate was concentrated under vacuum. The resulting oil residue was dissolved in CH_2Cl_2 (100 mL) and washed with H_2O (2 × 50 mL). The organic layer was separated from the aqueous layer and then dried over $MgSO_4$. After filtration, the solvent was removed in vacuo to yield crude 1,2-bis[2-[2-(2-hydroxyethoxy)ethoxy]ethoxy]benzene.

Without further purification, 4.4 M NaOH aq (25 mL) was added to the solution of 1,2-bis[2-[2-(2-hydroxyethoxy)ethoxy]ethoxy]-benzene in THF (25 mL). The stirred solution was cooled to 0 °C, and a solution of TsCl (13.3 g, 70.0 mmol) in THF (35 mL) was added dropwise over 20 min. Stirring was continued for an additional 1 day at room temperature, and then 2 N HCl (100 mL) was added. The mixture was extracted with toluene (2 × 100 mL). The organic layer was separated from the aqueous layer and washed with saturated $NaHCO_3$ aq (2 × 50 mL) and H_2O (2 × 50 mL). The organic layer was dried over $MgSO_4$. After filtration, the solvent was evaporated in vacuo. The residue was subjected to column chromatography on SiO_2 with CH_2Cl_2 and AcOEt (v/v = 80/1) as an eluent. The solvent was evaporated to obtain **4c** (15.5 g, 21.8 mmol, 73%) as a colorless oil. R_f = 0.60 (AcOEt). Spectroscopic data was consistent with those reported in the literature.[22]

Synthesis of 4d. 2,3-Dihydroxynaphthalene (4.81 g, 30.0 mol) and K_2CO_3 (12.4 g, 90.0 mol) were added to dry CH_3CN (100 mL). The resulting suspension was stirred vigorously, and 2-(2-chloroethoxy)-ethanol (11.2 g, 90.0 mol) was added dropwise. The reaction mixture was heated under reflux for 2 days. The purplish brown solution was filtered to remove K_2CO_3 and concentrated under reduced pressure. The residue was washed with CH_2Cl_2 (50 mL). The filtrate was concentrated under vacuum. The resulting oil residue was dissolved in CH_2Cl_2 (100 mL) and washed with H_2O (2 × 50 mL). The organic layer was separated from the aqueous layer and then dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The oil residue was allowed to stand at room temperature; after 30 min, 1,2-bis[2-(2-tosyloxyethoxy)ethoxy]naphthalene was obtained as a waxy solid (8.40 g, 24.9 mmol, 83%).

NaOH aq (4.0 M, 5 mL) was added to the solution of 1,2-bis[2-(2-tosyloxyethoxy)ethoxy]naphthalene (1.68 g, 5.0 mmol) in THF (20 mL). The stirred solution was cooled to 0 °C, and a solution of TsCl (2.86 g, 15.0 mmol) in THF (10 mL) was added dropwise over 20 min. Stirring was continued for an additional 1 day at room temperature, and then 2 N HCl (20 mL) was added. The mixture was extracted with toluene (2 × 50 mL). The organic layer was separated from the aqueous layer and washed with saturated $NaHCO_3$ aq (2 × 30 mL) and H_2O (2 × 30 mL). The organic layer was dried over $MgSO_4$. The solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with CH_2Cl_2 and AcOEt (v/v = 80/1) as an eluent. The solvent was evaporated to obtain **4d** (2.77 g, 4.30 mmol, 86%) as a white solid. R_f = 0.10 (CH_2Cl_2 and AcOEt, v/v = 80/1). Spectroscopic data were consistent with those reported in the literature.[23]

Synthesis of P-Stereogenic Diphosphacrowns. A typical procedure is as follows. A THF solution (25 mL) of (*S*,*S*)-**3** (117.0 mg, 0.50 mmol) was cooled to −78 °C under Ar atmosphere. Then, *n*-BuLi (1.6 M in *n*-hexane, 0.75 mL, 1.2 mmol) was added with a

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syringe. After being stirred for 1 h, a THF solution (25 mL) of ditosylate **4a** (253.3 mg, 0.50 mmol) was added with a syringe. The reaction mixture was allowed to warm to room temperature. After being stirred for 48 h, the reaction was quenched by addition of 2 N HCl aq (20 mL). The organic layer was extracted with AcOEt (3 × 50 mL). The combined organic layers were washed with saturated $NaHCO_3$ aq and brine and dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with AcOEt and hexane (v/v = 1/2) as an eluent. After removal of solvent, the residue was purified by preparative HPLC. The solvent was removed in vacuo to give (*R*,*R*)-**5a** (55.2 mg, 0.14 mmol, 28%) as colorless solid.

(*R*,*R*)-5a: R_f = 0.70 (AcOEt and hexane, v/v = 1/1); $[\alpha]_D^{23}$ = +59.6 (*c* 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz δ 0.36 (br q, J_{H-B} = 110.7 Hz, 6H), 1.19 (d, J_{H-P} = 13.3 Hz, 18H), 1.92−2.59 (m, 8H), 4.32−4.48 (m, 8H), 6.80−6.93 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 15.3 (d, J_{C-P} = 31.2 Hz), 21.6 (d, J_{C-P} = 30.4 Hz), 25.5, 28.6 (d, J_{C-P} = 34.4 Hz), 63.2, 111.9, 121.3, 147.4 ppm; ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ +32.3 (br d, J_{P-B} = 51.4 Hz) ppm; HRMS (ESI): calcd for $C_{20}H_{40}B_2O_2P_2$ $[M + Na]^+$ 419.2582, found 419.2570. Anal. Calcd for $C_{20}H_{40}B_2O_2P_2$: C, 60.64; H, 10.18. Found: C, 60.42; H, 10.44.

(*R*,*R*)-5b: yield 62% (300.0 mg 0.62 mmol), colorless solid; R_f = 0.65 (AcOEt and hexane, v/v = 1/1); $[\alpha]_D^{23}$ = +25.4 (*c* 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz δ 0.36 (br q, J_{H-B} = 113.9 Hz, 6H), 1.15 (d, J_{H-P} = 13.5 Hz, 18H), 1.80−2.08 (m, 8H), 3.75−3.91 (m, 8H), 4.09−4.23 (m, 4H), 6.86−6.95 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 15.2 (d, J_{C-P} = 30.8 Hz), 21.3 (d, J_{C-P} = 29.8 Hz), 25.1, 28.4 (d, J_{C-P} = 33.1 Hz), 66.3, 68.7, 69.9, 115.3, 121.8, 149.2 ppm; ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ +32.3 (br d, J_{P-B} 49.4 Hz) ppm; HRMS (FAB) calcd for $C_{24}H_{48}B_2O_4P_2$ $[M - H]^+$ 483.3136, found 483.3155. Anal. Calcd for $C_{24}H_{48}B_2O_4P_2$: C, 59.53; H, 9.99. Found: C, 59.25; H, 10.00.

(*R*,*R*)-5c: yield 43% (123.8 mg, 0.22 mmol), colorless solid; R_f = 0.17 (AcOEt and hexane, v/v = 1/1); $[\alpha]_D^{23}$ = +8.5 (*c* 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz δ 0.36 (br q, J_{H-B} = 117.1 Hz, 6H), 1.16 (d, J_{H-P} = 13.6 Hz, 18H), 1.82−2.06 (m, 8H), 3.59−3.68 (m, 4H), 3.71−3.81 (m, 8H), 3.86−3.90 (m, 4H), 6.87−6.93 (m, 4H) ppm;^{13}C NMR ($CDCl_3$, 100 MHz) δ 15.2 (d, J_{C-P} = 30.6 Hz, PCH_2), 21.3 (d, J_{C-P} = 30.8 Hz, PCH_2), 25.2, 28.5 (d, J_{C-P} = 33.9 Hz), 66.2, 69.2, 69.7, 70.3, 70.6, 114.6, 121.6, 149.0 ppm; ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ +32.4 (br d, J_{P-B} = 36.4 Hz) ppm; HRMS (ESI) calcd for $C_{28}H_{56}B_2O_6P_2$ $[M + Na]^+$ 595.3630, found 595.3610. Anal. Calcd for $C_{28}H_{56}B_2O_6P_2$: C, 58.76; H, 9.86, found: C, 58.54; H, 9.69.

(*R*,*R*)-5d: yield 69% (147.3 mg, 0.28 mmol), colorless solid; R_f = 0.65 (AcOEt and hexane, v/v = 1/1); $[\alpha]_D^{23}$ = +44.8 (*c* 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz δ 0.36 (br q, J_{H-B} = 111.2 Hz, B*H*$_3$, 6H), 1.15 (d, J_{H-P} = 13.7 Hz, 18H), 1.84−2.05 (m, 8H), 3.81−3.97 (m, 8H), 4.22−4.26 (m, 4H), 7.13 (s, 2H), 7.30−7.35 (m, 2H), 7.64−7.67 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 15.2 (d, J_{C-P} = 30.6 Hz,), 21.3 (d, J_{C-P} = 30.2 Hz), 25.2, 28.4 (d, J_{C-P} = 34.1 Hz), 66.4, 68.1, 69.6, 108.8, 124.4, 126.3, 129.3, 149.1 ppm; ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ +32.3 (br d, J_{P-B} = 35.0 Hz) ppm; HRMS (ESI) calcd for $C_{28}H_{50}B_2O_4P_2$ $[M + NH_4]^+$ 552.3709, found 552.3699. Anal. Calcd for $C_{28}H_{50}B_2O_4P_2$: C, 62.95; H, 9.43. Found: C, 62.75; H, 9.71.

(*R*,*R*)-5e: yield 64% (140.3 mg, 0.32 mmol), colorless solid; R_f = 0.13 (AcOEt and hexane, v/v = 1/1); $[\alpha]_D^{23}$ = +10.5 (*c* 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz δ 0.35 (br q, J_{H-B} = 116.0 Hz, 6H), 1.17 (d, J_{H-P} = 13.4 Hz, 18H), 1.85−2.02 (m, 8H), 3.59−3.81 (m, 16H) ppm; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 15.2 (d, J_{C-P} = 30.4 Hz), 21.3 (d, J_{C-P} = 30.8 Hz), 25.3, 28.5 (d, J_{C-P} = 34.1 Hz), 66.3, 70.4, 70.5, 70.9 ppm; ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ +32.1 (br d, J_{P-B} 54.9 Hz) ppm; HRMS (ESI) calcd for $C_{20}H_{48}B_2O_4P_2$ $[M + Na]^+$ 459.3106, found 459.3087. Anal. Calcd for $C_{20}H_{48}B_2O_4P_2$: C, 55.07; H, 11.09. Found: C, 54.89; H, 11.25.

Synthesis of (*R*,*R*)-2. An Et_2O solution (200 mL) of (*S*,*S*)-**6** (917.0 mg, 3.5 mmol) and TMEDA (1.10 mL, 7.0 mmol) was cooled to −78 °C under Ar atmosphere. *s*-BuLi (1.0 M in cyclohexane and *n*-hexane, 7.0 mL, 7.0 mmol) was added via syringe. After the solution was stirred for 3 h, dry O_2 was bubbled into the reaction mixture. The reaction mixture was allowed to warm to room temperature and stirred overnight. The reaction was quenched by addition of 2 N HCl aq (100 mL). The organic layer was extracted with AcOEt (3 × 100 mL). The combined organic layers were washed with brine and dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with AcOEt and hexane (v/v = 1/3) as an eluent, and recrystallization from toluene gave (*R*,*R*)-**2** (367.5 mg, 1.25 mmol, 36%) as a colorless solid. $[\alpha]_D^{21}$ = −5.7 (*c* 0.5, $CHCl_3$). Spectroscopic data was consistent with those of enantiomer (*S*,*S*)-**2**.

Synthesis of (*R*,*R*)-3. An aqueous solution (30 mL) of KOH (2.24 g, 40 mmol) and $K_2S_2O_8$ (3.24 g, 12 mmol) was cooled to 0 °C. After addition of $RuCl_3{\cdot}nH_2O$ (104.6 mg, 0.40 mmol) to the aqueous solution, an acetone solution (20 mL) of (*R*,*R*)-**2** (588.0 mg, 2.0 mmol) was added dropwise. The reaction mixture was allowed to warm to room temperature. After stirring for 4 h, the reaction was quenched by addition of 2 N HCl aq (50 mL). The organic layer was extracted with Et_2O (3 × 100 mL). The combined organic layers were washed with brine and dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with AcOEt and hexane (v/v = 1/2) as an eluent, and recrystallization from toluene and hexane gave (*R*,*R*)-**3** (381.5 mg, 1.63 mmol, 82%) as a colorless solid. $[\alpha]_D^{21}$ = +86.0 (*c* 0.5, $CHCl_3$). Spectroscopic data was consistent with those of enantiomer (*S*,*S*)-**3**.

Synthesis of (*S*,*S*)-5b. The synthetic procedure was same as that of (*R*,*R*)-**5a**−**e**: yield 59% (142.8 mg, 0.30 mmol), colorless solid; $[\alpha]_D^{23}$ = −22.4 (*c* 0.5, $CHCl_3$). Spectroscopic data were consistent with those of enantiomer (*R*,*R*)-**5b**.

Synthesis of (*rac*)-5b. The synthetic procedure was same as that of (*R*,*R*)-**5b**: yield 42% (102.4 mg, 0.21 mmol), colorless solid. Spectroscopic data were consistent with those of enantiomer (*R*,*R*)-**5b**.

Deboranation of (*R*,*R*)-5b and Complexation with $PtCl_2$(cod). (*R*,*R*)-**5b** (24.4 mg, 0.050 mmol) was dissolved in morpholine (3 mL) under Ar. After the solution was stirred for 2 days at 50 °C, the solvent was dried in vacuo to give (*R*,*R*)-**5b**′. The reaction proceeded quantitatively, which was estimated by ^{31}P NMR: ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ −1.1 ppm.

To the solution of (*R*,*R*)-**5b**′ in degassed $CHCl_3$ was added $PtCl_2$(cod) (18.7 mg, 0.050 mmol) in one portion. After the solution was stirred for 1 day at room temperature, the solvent was dried in vacuo. The residue was purified by preparative HPLC. The solvent was removed in vacuo, and recrystallization from $CHCl_3$ and hexane gave $PtCl_2$[(*R*,*R*)-**5b**′] as a colorless solid (13.4 mg, 0.019 mmol, 37%): $[\alpha]_D^{21}$ = +143.6 (*c* 0.25, $CHCl_3$). ^{1}H NMR ($CDCl_3$, 400 MHz δ 1.43 (d, J_{H-P} = 15.2 Hz, 18H), 1.57−1.62 (m, 2H), 2.34−2.57 (m, 4H), 2.82−3.04 (m, 2H), 3.74−3.90 (m, 8H), 4.10−4.22 (m, 4H), 6.85−6.95 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 22.9 (d, J_{C-P} = 27.9 Hz), 23.6 (dd, J_{C-P} = 36.0, 4.3 Hz), 28.2, 32.7 (d, J_{C-P} = 37.0 Hz), 66.6, 67.0, 68.8, 111.4, 120.9, 147.6 ppm; ^{31}P{^{1}H}NMR ($CDCl_3$, 161.9 MHz) δ +55.3 (J_{P-Pt} = 3609 Hz) ppm; HRMS (ESI) calcd for $C_{24}H_{42}O_4P_2Cl_2Pt$ $[M - Cl]^+$ 686.1889, found 686.1859. Anal. Calcd for $C_{24}H_{42}O_4P_2Cl_2Pt$: C, 39.65; H, 5.86. Found: C, 39.90; H, 5.86.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H, ^{13}C, and ^{31}P NMR spectra of (*R*,*R*)-**5a**−**e**. Chiral HPLC charts of (*R*,*R*)-**5b**, (*S*,*S*)-**5b**, and (*rac*)-**5b**. X-ray crystallographic data of (*R*,*R*)-**5a**−**c**. Deboranation and complexation scheme of (*R*,*R*)-**5b**. ^{1}H, ^{13}C, and ^{31}P NMR spectra and X-ray crystallographic data of the Pt complex. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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