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Synthesis of Enantiomerically Pure P-Stereogenic Diphosphacrowns and Their Palladium Complexes

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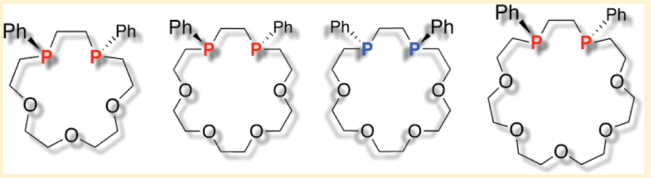
Supporting Information

ABSTRACT: A practical synthetic route for enantiomerically pure P-stereogenic diphosphacrowns was developed by using a P-stereogenic bisphosphine as a chiral building block. Their molecular structures were confirmed by NMR spectroscopy and X-ray crystallography. Complexation of the diphosphacrowns with palladium was carried out, and the corresponding palladium complexes were obtained. The P-stereogenic diphosphacrowns were applicable to the chiral ligand for the asymmetric 1,4-addition of arylboronic acids to α,β-unsaturated ketone catalyzed by palladium. This reaction proceeded smoothly to afford the corresponding 1,4-addition products in high yield with good enantioselectivities.



INTRODUCTION

Crown ethers are macrocyclic compounds comprising a ring with several ether groups. The most common crown ethers have ethyleneoxy (−CH_2CH_2−O−) repeating units in their ring skeletons, which can wrap and capture various metal cations as well as cationic molecules owing to the presence of lone pair(s) of oxygen atoms.[1,2] A ground-breaking and simple method of synthesizing crown ethers was discovered by Pederson in 1967.[1] Subsequently, after his seminal work, crown ether chemistry was developed further for diverse molecular systems.[3−5] This research made it possible to realize host−guest chemistry[6] that can be said to be the cornerstone of supramolecular chemistry.[7]

Since the first report on the synthesis of dibenzo-18-crown-6,[1] numerous other crown ether derivatives have been reported. Further, in many crown ether derivatives, the oxygen atoms have been replaced by various heteroatoms. For example, azacrowns[2c] and thiacrowns[2d,2e] comprise "−CH_2CH_2−NR−" and "−CH_2CH_2−S−" repeating units, respectively, in addition to the "−CH_2CH_2−O−" units; the guest selectivities and binding strengths of these derivatives are different from those of crown ethers. Phosphacrowns are an identical class of crown ether derivatives containing phosphorus atoms instead of oxygen atoms;[2f−2h] however, they have not attracted much attention thus far. In fact, to our knowledge, there are no examples of the synthesis of P-stereogenic phosphacrowns possessing chiral phosphorus atoms, even though a phosphorus atom can be a chiral center owing to its high inversion energy. On the other hand, the optical resolution of racemic phosphorus-containing macrocycles has been achieved previously by employing a procedure that leads to the spontaneous crystallization of the racemic macrocycle−Ni complex; the enantiomers are then separated by Pasteur's method.[8]

Recently, we have successfully prepared P-stereogenic (*S*,*S*)- and (*R*,*R*)-18-diphosphacrown-6 containing two chiral phosphorus atoms in the ring by using P-stereogenic (*S*,*S*)- and (*R*,*R*)-bisphosphine−boranes as the building blocks, respectively.[9] This is the first example of the synthesis of P-stereogenic diphosphacrowns possessing chiral heteroatoms (phosphorus atoms) in the ring structure. This synthetic strategy makes it possible to prepare various P-stereogenic diphosphacrowns. In this study, we describe the synthesis and characterization of enantiomerically pure P-stereogenic diphosphacrowns with various ring sizes in detail. One of our motivations is also to apply the P-stereogenic diphosphacrowns to a chiral ligand for realizing transition metal-catalyzed asymmetric reactions. After many trials, we have found an effective catalytic system for the asymmetric 1,4-addition of arylboronic acids to enones. Thus, herein, we also report the asymmetric 1,4-addition of arylboronic acids to cyclic α,β-unsaturated ketones catalyzed using P-stereogenic diphosphacrown-cationic palladium(II) complexes as well.

RESULTS AND DISCUSSION

To prepare the enantiomerically pure P-stereogenic diphosphacrowns, the P-stereogenic precursor (*S*,*S*)-**3**−BH_3 was synthesized from (*S*,*S*)-**1**−BH_3 as shown in Scheme 1. The synthetic method of (*S*,*S*)-**1**−BH_3 was established by Evans and co-workers,[10a] and it was recently modified by us to yield (*S*,*S*)-**1**−BH_3 with > 99% ee.[10b] The methyl group substituted at a borane-coordinated phosphorus atom can be lithiated by alkyllithium reagents such as *sec*-BuLi, and this enables us to prepare various P-stereogenic phosphines having different functional groups. Thus, the dilithiation of the

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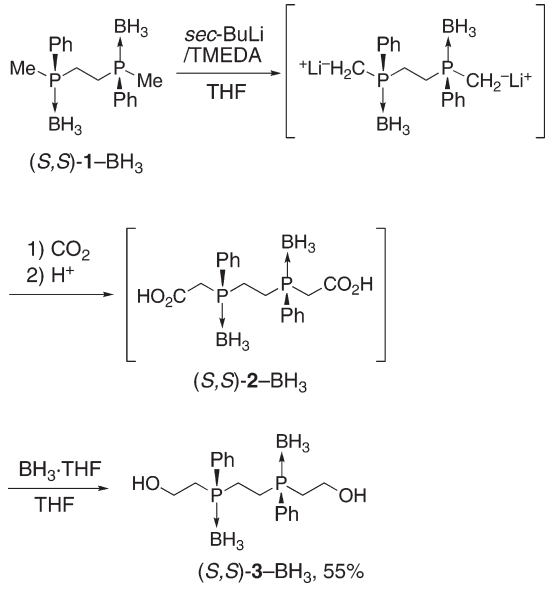
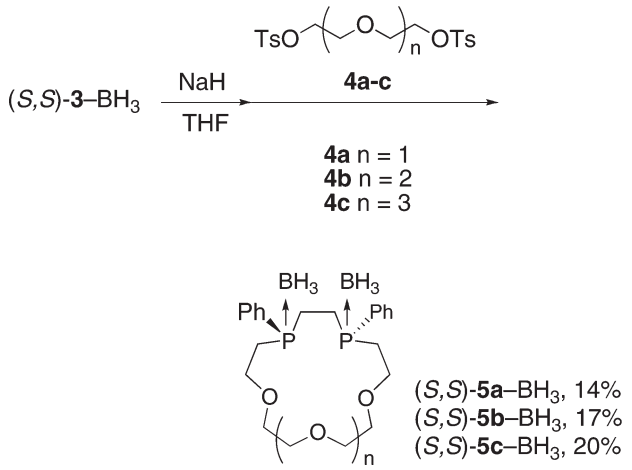
Scheme 1. Synthesis of (*S*,*S*)-3−BH_3



Scheme 2. Synthesis of (*S*,*S*)-5a−c−BH_3



two methyl groups in (*S*,*S*)-**1**−BH_3 was easily performed with *sec*-BuLi/*N*,*N*,*N*′,*N*′-tetramethylenediamine (TMEDA), and the successive reaction with dry CO_2 gas afforded the P-stereogenic dicarboxylic acid (*S*,*S*)-**2**−BH_3. Without purification, the carboxylic groups in (*S*,*S*)-**2**−BH_3 were reduced with BH_3·THF to give the target precursor (*S*,*S*)-**3**−BH_3 in 55% isolated yield.

The P-stereogenic diphosphacrowns were obtained according to Scheme 2 by the Williamson ether synthesis. The reaction was carried out under diluted condition (20 mM of each substrate in THF). The treatment of (*S*,*S*)-**3**−BH_3 with NaH and ethyleneglycol bis(*p*-toluenesulfonate)s **4a**−**c** afforded the corresponding (*S*,*S*)-15-diphosphacrown-5−BH_3 "(*S*,*S*)-**5a**−BH_3", (*S*,*S*)-18-diphosphacrown-6−BH_3 "(*S*,*S*)-**5b**−BH_3", and (*S*,*S*)-21-diphosphacrown-7−BH_3 "(*S*,*S*)-**5c**−BH_3", respectively. Further, the diphosphacrowns could be readily purified by open SiO_2 column chromatography, and (*S*,*S*)-**5a**−**c**−BH_3 were obtained as colorless solids in 14%, 17%, and 20% isolated yields, respectively.

The enantiomers (*R*,*R*)-diphosphacrowns (*R*,*R*)-**5a**−**c**−BH_3 can be prepared from the corresponding P-stereogenic dialcohol (*R*,*R*)-**3**−BH_3; however, its straightforward synthesis is challenging, because the precursor (*R*,*R*)-**1**−BH_3 has to be prepared with (+)-sparteine[11] (Scheme 3). Therefore, we attempted the synthesis of (*R*,*R*)-18-diphosphacrown-6−BH_3 "(*R*,*R*)-**5b**−BH_3" as a representative example, as shown in Scheme 4. One methyl group of dimethylphenylphosphine−borane **6**−BH_3 was enantioselectively lithiated with *sec*-BuLi/(−)-sparteine, which was treated with dry CO_2 gas and H^+ to yield the corresponding carboxylic acid. BH_3·THF reduced the carboxylic group and provided (*S*)-**7**−BH_3 in 71% isolated yield with 87% ee; the estimations were performed by high performance liquid chromatography (HPLC), using a chiral column (Figure S1 in the Supporting Information).[12] Another methyl group in (*S*)-**7**−BH_3 was reacted with *sec*-BuLi/TMEDA. After the treatment with $CuCl_2$ and aqueous NH_3, repeated recrystallizations with toluene and hexane afforded (*R*,*R*)-**3**−BH_3 in 36% yield.[13] The formation of the dialkoxide of (*R*,*R*)-**3**−BH_3 with NaH followed by the reaction with triethyleneglycol bis(*p*-toluenesulfonate) **4b** gave the desired enantiomer (*R*,*R*)-**5b**−BH_3 in 22% yield.

The chemical structures of the P-stereogenic compounds were confirmed by measuring ^1H, ^{13}C, and $^{31}P\{^1H\}$ NMR spectra (Supporting Information). As an example, the ^1H NMR spectrum of (*S*,*S*)-**5b**−BH_3 exhibits a broad signal of two BH_3 groups at around 0.7 ppm that is split into a quartet by the boron atom with J_{H-B} of 119.4 Hz (Figure S9, Supporting Information). A relatively sharp $^{31}P\{^1H\}$ signal of (*S*,*S*)-**5b**−BH_3 appeared at δ 16.5 ppm, which was also split into a quartet (J_{P-B} = 38.4 Hz) by the coordination of BH_3 (Figure S11, Supporting Information). The $^{31}P\{^1H\}$ signals of (*S*,*S*)-**5a**−BH_3 and (*S*,*S*)-**5c**−BH_3 showed the expected peak at δ +17.7 and +16.3 ppm, respectively, as shown in Figures S8 and S14 (Supporting Information). The $[\alpha]_D$ values of (*S*,*S*)-**5a**−**c**−BH_3 were found to be $[\alpha]^{25}_D$ +103.0 (*c* 0.5 in $CHCl_3$), +62.7 (*c* 1.0 in $CHCl_3$), and +50.2 (*c* 0.5 in $CHCl_3$), respectively; these values were considerably larger than that of (*S*,*S*)-**3**−BH_3 ($[\alpha]^{22}_D$ +9.1, *c* 1.0 in $CHCl_3$). This is because, in addition to the chirality of the two phosphorus atoms, cyclization causes new chirality in the ring structure.

Single crystals of (*S*,*S*)-**5a**−BH_3 and (*S*,*S*)-**5b**−BH_3 could be successfully obtained by recrystallization from CH_2Cl_2 and hexane. Their molecular structures were confirmed by X-ray crystallography. The ORTEP drawings are shown in Figures 1 and 2. The selected bond distances and bond angles of (*S*,*S*)-**5a**−BH_3 and (*S*,*S*)-**5b**−BH_3 are listed in Tables 1 and 2, respectively. The structure of each diphosphacrown can be rationalized as being the expected absolute configuration comprising (*S*)-phosphorus atoms. As shown in Figure 1, (*S*,*S*)-**5a**−BH_3 adopted one conformation in the crystal, whereas (*S*,*S*)-**5b**−BH_3 existed as two conformations (Figure 2). Further, one conformer possessed two phenyl groups on the side opposite to the diphosphacrown ring (side view a in Figure 2), while the other possessed two phenyl groups above the ring (side view b in Figure 2). On the other hand, the $^{31}P\{^1H\}$ NMR spectrum of (*S*,*S*)-**5b**−BH_3 exhibited a single signal with J_{P-B} of 38.4 Hz (vide supra), as shown in Figure S11 (Supporting Information), indicating that the ring structure of (*S*,*S*)-**5b**−BH_3 was flexible, and rapid interconversion of the two conformers occurred in the solution.

The average phosphorus−carbon and oxygen−carbon bond lengths of the ring structure in (*S*,*S*)-**5a**−BH_3 were found to be 1.830 and 1.424 Å (Table 1), respectively. The average angles between the segments joining a central phosphorus atom and

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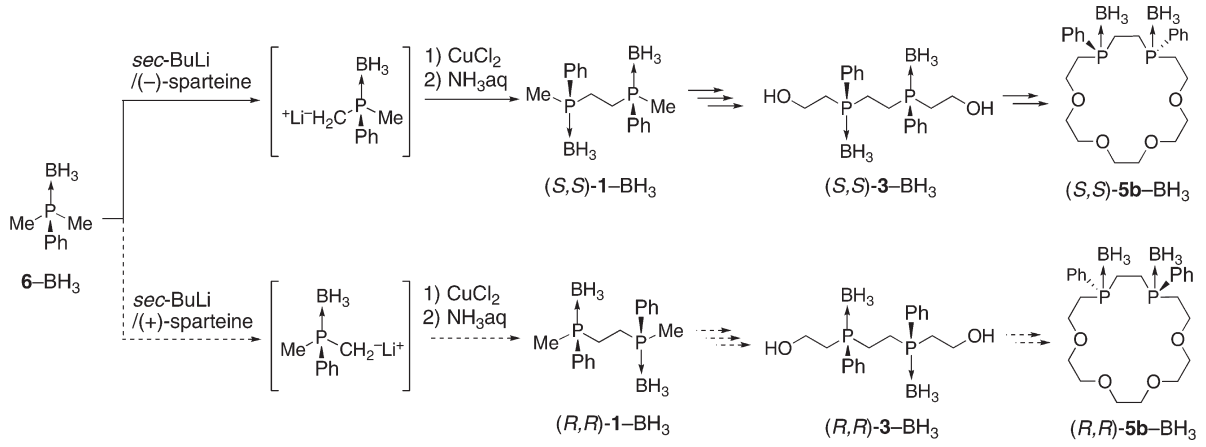
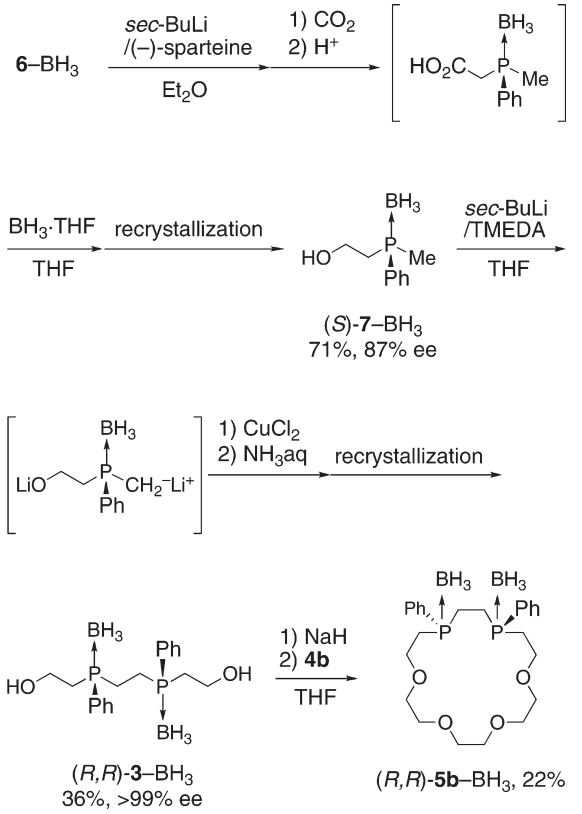
Scheme 3. Synthetic Route for (*S,S*)-3−BH_3 and (*R,R*)-3−BH_3



Scheme 4. Synthesis of (*R,R*)-3−BH_3 and (*R,R*)-5b−BH_3



three vertex atoms in (*S,S*)-**5a**−BH_3 were 109.4° and 109.3° for P(1) and P(2), respectively, as listed in Table 1. This suggests that each phosphorus atom is located at the center of a tetrahedral molecular geometry with a small distortion. The bond lengths and bond angles around the phosphorus atoms in both conformers of (*S,S*)-**5b**−BH_3 were almost identical with those of (*S,S*)-**5a**−BH_3 (Table 2). The ring sizes of (*S,S*)-**5a**−BH_3 and (*S,S*)-**5b**−BH_3 are slightly larger than those of 15-crown-5 and 18-crown-6, respectively. Although the single crystal of (*S,S*)-**5c**−BH_3 suitable for X-ray crystallography could not be obtained, its ring size can be expected to be slightly larger than that of 21-crown-7.

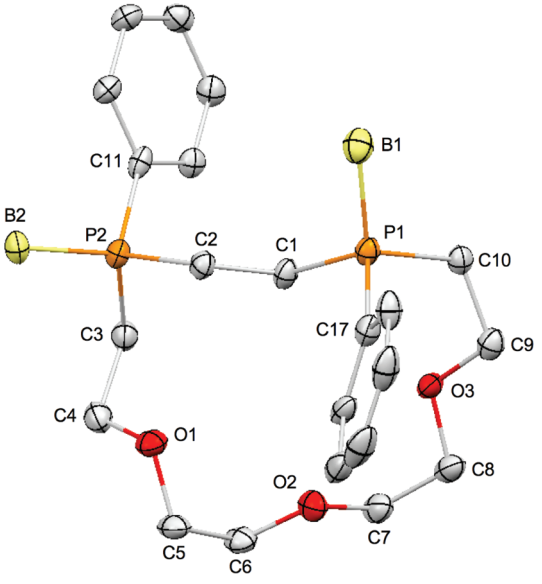


Figure 1. ORTEP drawing of (*S,S*)-**5a**−BH_3. Thermal ellipsoids are drawn at the 30% probability level. Hydrogen atoms are omitted for clarity.

The complexations of P-stereogenic diphosphacrowns (*S,S*)-**5a**−**c**−BH_3 with palladium(II) were carried out with $PdCl_2$(cod) (cod = 1,5-cyclooctadiene) as a precursor. The coordinated boranes of (*S,S*)-**5a**−**c**−BH_3 were readily removed by treating with a strong organic base such as 1,4-diazabicyclo[2.2.2]octane (DABCO), as shown in Scheme 5. The solvent was dried, and the crude product was subjected to a SiO_2 short column chromatography. The obtained diphosphacrowns (*S,S*)-**5a**−**c** were used for the subsequent complexation without further purification. The reactions of (*S,S*)-**5b** and (*S,S*)-**5c** with $PdCl_2$(cod) in $CHCl_3$ proceeded smoothly to afford the corresponding diphosphacrown−palladium complexes **8b** and **8c** in 69% and 74% isolated yields, respectively.[14] However, almost no reaction occurred with (*S,S*)-**5a**.

The structures of **8b** and **8c** were deduced on the basis of ^1H, ^{13}C, and $^{31}P\{^1H\}$ NMR analysis. $^{31}P\{^1H\}$ NMR signals of phosphine−borane of (*S,S*)-**5b**−BH_3 and (*S,S*)-**5c**−BH_3

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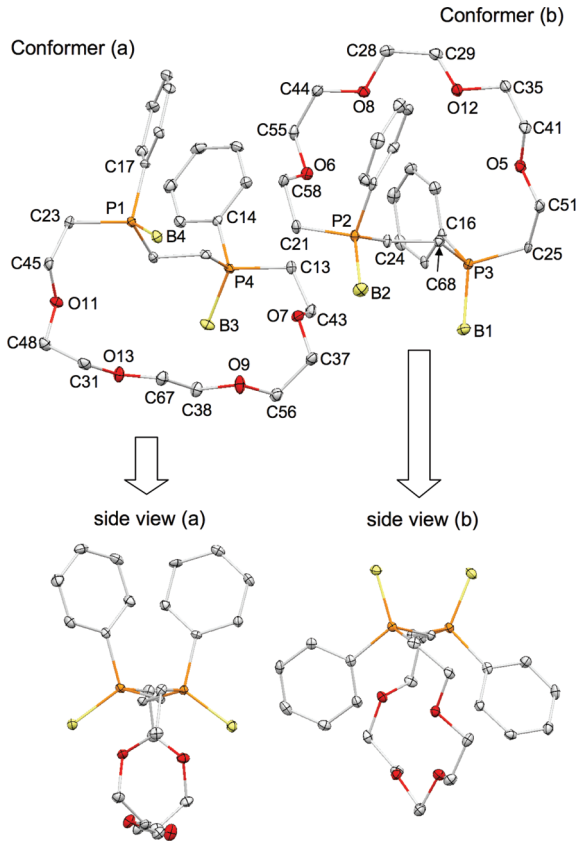


Figure 2. ORTEP drawings of (*S,S*)-**5b**−BH_3 (conformers a and b). Thermal ellipsoids are drawn at the 30% probability level. Hydrogen atoms are omitted for clarity.

Table 1. Selected Bond Distances (Å) and Angles (deg) in (*S,S*)-5a−BH_3

Bond Distances			
P(1)−C(1)	1.817(5)	O(1)−C(4)	1.428(7)
P(1)−C(10)	1.845(5)	O(1)−C(5)	1.431(6)
P(2)−C(2)	1.830(5)	O(2)−C(6)	1.416(6)
P(2)−C(3)	1.828(5)	O(2)−C(7)	1.427(6)
		O(3)−C(8)	1.430(7)
		O(3)−C(9)	1.412(7)
Bond Angles			
C(1)−P(1)−C(10)	105.0(2)	C(2)−P(2)−C(3)	107.8(2)
C(1)−P(1)−C(17)	106.7(2)	C(2)−P(2)−C(11)	104.9(2)
C(10)−P(1)−C(17)	108.6(2)	C(3)−P(2)−C(11)	104.5(2)
B(1)−P(1)−C(1)	113.0(3)	B(2)−P(2)−C(2)	111.0(2)
B(1)−P(1)−C(10)	111.5(3)	B(2)−P(2)−C(3)	115.2(3)
B(1)−P(1)−C(17)	111.6(3)	B(2)−P(2)−C(11)	112.8(2)

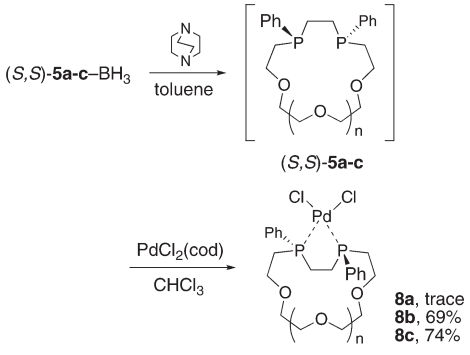
disappeared completely, while sharp singlet signals of the phosphorus atoms of **8b** and **8c** could be observed at δ 72.1 and 71.0 ppm (Figures S20 and S23, Supporting Information), respectively. Complexes **8b** and **8c** had negative $[\alpha]_D$ values of $[\alpha]^{22}_D$ −122.6 (*c* 1.0 in $CHCl_3$) and $[\alpha]^{22}_D$ −110.0 (*c* 1.0 in $CHCl_3$), respectively.

Air-stable crystals of **8b** and **8c** suitable for X-ray crystallography were obtained by recrystallization from CH_2Cl_2 and

Table 2. Selected Bond Distances (Å) and Angles (deg) in (*S,S*)-5b−BH_3

Bond Distances			
conformer a		conformer b	
P(1)−C(17)	1.820(3)	P(2)−C(21)	1.817(4)
P(1)−C(20)	1.827(4)	P(2)−C(24)	1.810(4)
P(1)−C(23)	1.821(4)	P(2)−C(42)	1.812(5)
P(1)−B(4)	1.907(5)	P(2)−B(2)	1.916(5)
P(4)−C(13)	1.829(4)	P(3)−C(16)	1.810(4)
P(4)−C(14)	1.812(3)	P(3)−C(25)	1.831(4)
P(4)−C(34)	1.827(4)	P(3)−C(68)	1.816(4)
P(4)−B(3)	1.910(5)	P(3)−B(1)	1.917(4)
O(7)−C(37)	1.431(5)	O(5)−C(41)	1.426(6)
O(7)−C(43)	1.425(5)	O(5)−C(51)	1.423(5)
O(9)−C(38)	1.401(5)	O(6)−C(55)	1.421(4)
O(9)−C(56)	1.415(6)	O(6)−C(58)	1.430(5)
O(11)−C(45)	1.422(6)	O(8)−C(28)	1.422(5)
O(11)−C(48)	1.412(4)	O(8)−C(44)	1.416(5)
O(13)−C(31)	1.410(5)	O(12)−C(29)	1.427(5)
O(13)−C(67)	1.406(5)	O(12)−C(35)	1.424(5)
Bond Angles			
conformer a		conformer b	
C(23)−P(1)−C(20)	110.0(2)	C(24)−P(2)−C(21)	104.8(2)
C(17)−P(1)−C(20)	103.8(2)	C(24)−P(2)−C(42)	107.5(2)
C(23)−P(1)−C(17)	103.2(2)	C(21)−P(2)−C(42)	106.9(2)
B(4)−P(1)−C(17)	112.5(2)	B(2)−P(2)−C(21)	111.9(2)
B(4)−P(1)−C(20)	113.4(2)	B(2)−P(2)−C(24)	110.6(2)
B(4)−P(1)−C(23)	113.1(2)	B(2)−P(2)−C(42)	114.5(2)
C(34)−P(4)−C(13)	105.3(2)	C(68)−P(3)−C(25)	107.1(2)
C(14)−P(4)−C(13)	107.7(2)	C(25)−P(3)−C(16)	109.7(2)
C(14)−P(4)−C(34)	106.5(2)	C(16)−P(3)−C(68)	104.1(2)
B(3)−P(4)−C(13)	113.4(2)	B(1)−P(3)−C(16)	113.6(2)
B(3)−P(4)−C(14)	111.7(2)	B(1)−P(3)−C(25)	110.3(2)
B(3)−P(4)−C(34)	114.5(2)	B(1)−P(3)−C(68)	111.8(2)

Scheme 5. Synthesis of Palladium Complexes 8a−c



hexane. The results are shown in Figures 3 and 4, and the selected bond lengths and angles are listed in Tables 3 and 4, respectively. Figure 3 shows the ORTEP drawings of **8b**, and diphosphacrown (*S,S*)-**5b** coordinated with palladium outside the ring as a bidentate ligand. The P−Pd−P, P−Pd−Cl, and Cl−Pd−Cl

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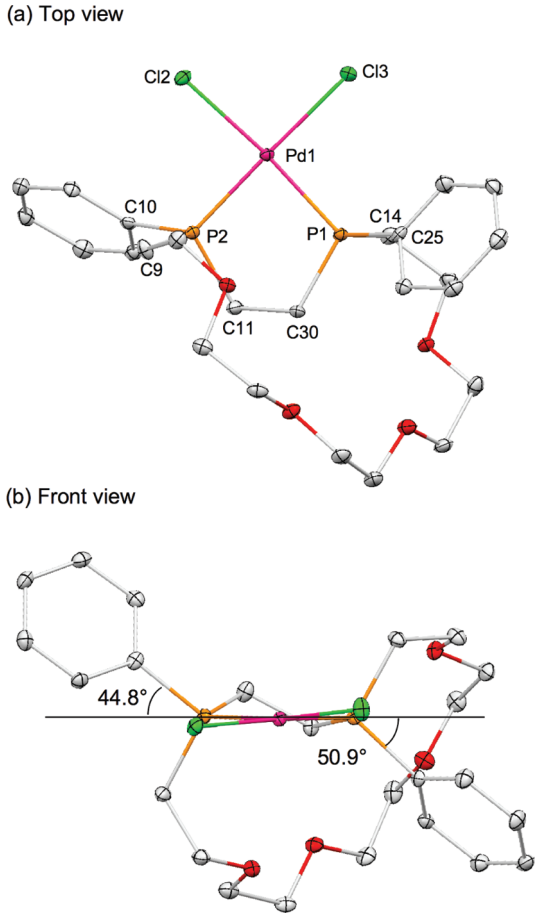

Figure 3. ORTEP drawings of **8b**. Thermal ellipsoids are drawn at the 30% probability level. Hydrogen atoms are omitted for clarity.

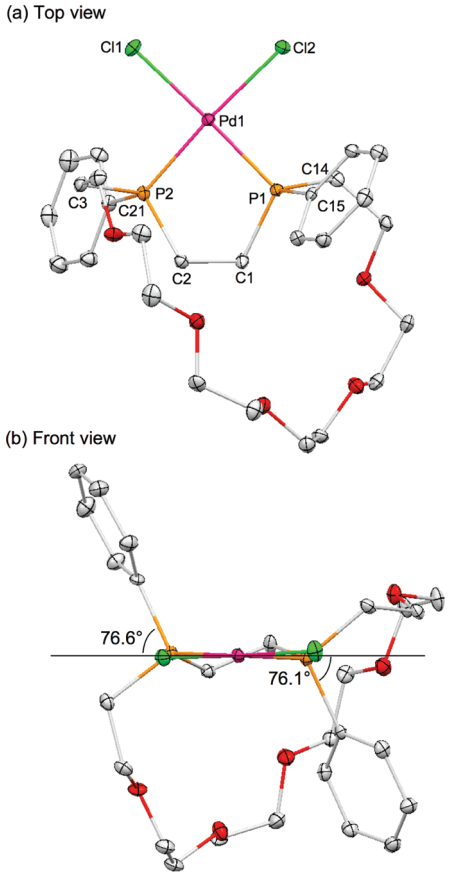

Figure 4. ORTEP drawings of **8c**. Thermal ellipsoids are drawn at the 30% probability level. Hydrogen atoms and $CHCl_3$ are omitted for clarity.

angles in **8b** and **8c** were around 90°, and the sum of the angles was 360.3° and 360.2°, respectively; this indicates a square-planar environment for palladium (top views in Figures 3 and 4). In Figure 3, two phenyl groups of **8b** were located at two diagonal quadrants and occupy quasi-equatorial positions (front view). This is similar to the case of a series of rhodium−(P-stereogenic bisphosphine) complexes.[15] The dihedral angles of the phenyl groups were 44.8° and 50.9° (front view in Figure 3). On the other hand, the coordination of (*S*,*S*)-**5c** to palladium created a different asymmetric environment from (*S*,*S*)-**5b**. Figure 4 shows the ORTEP drawings of **8c**. The P-stereogenic 21-diphospha-crown-7 skeleton could be confirmed, although single crystals of (*S*,*S*)-**5c**−BH_3 could not be produced. In Figure 4, palladium in **8c** existed outside the ring, similarly to **8b**, and the two phenyl groups occupied quasi-axial positions in the crystal. The dihedral angles of the phenyl groups were 76.6° and 76.1° (front view in Figure 4). Lippard and co-workers have previously reported the isolation of (*rac*)-**5c** from a mixture of *anti*-**5c** (racemic) and *syn*-**5c** (meso), and the X-ray structure of racemic palladium complex has also been revealed.[8] This structure also suggested that two phenyl groups were located at quasi-axial positions.

In a subsequent study, we focused on the application of the P-stereogenic diphosphacrown to a chiral ligand for performing transition metal-catalyzed asymmetric reactions. Among them, we selected catalytic asymmetric 1,4-additions,[16−19] because palladium-catalyzed asymmetric 1,4-additions of arylboronic acids to α,β-unsaturated ketones are relatively rare.[17] Asymmetric

Table 3. Selected Bond Distances (Å) and Angles (deg) in 8b

Bond Distances			
Pd(1)−P(1)	2.2476(8)	Pd(1)−Cl(2)	2.3514(8)
Pd(1)−P(2)	2.2326(8)	Pd(1)−Cl(3)	2.3705(9)
Bond Angles			
P(1)−Pd(1)−P(2)	86.47(3)	C(25)−P(1)−C(14)	104.6(1)
P(2)−Pd(1)−Cl(2)	88.83(3)	C(30)−P(1)−C(25)	106.5(1)
Cl(2)−Pd(1)−Cl(3)	92.78(3)	C(10)−P(2)−Pd(1)	118.2(1)
Cl(3)−Pd(1)−P(1)	92.22(3)	C(11)−P(2)−Pd(1)	107.3(1)
C(30)−P(1)−Pd(1)	108.2(1)	C(9)−P(2)−C(10)	101.9(1)
C(14)−P(1)−Pd(1)	110.4(1)	C(11)−P(2)−C(9)	106.9(1)

1,4-addition of arylboronic acids to 2-cyclopentenone was examined in the presence of several palladium/P-stereogenic bisphosphine/$AgSbF_6$ catalytic systems; the results are summarized in Table 5. An appropriate catalyst combined with P-stereogenic bisphosphine was critically important for the success of the reaction. For example, no catalytic activity of $PdCl_2$(cod)/(*S*,*S*)-**5a** was observed (run 1 in Table 5). Considering that palladium complex **8a** did not form in the complexation study described above, no active species for the 1,4-addition were generated in situ in the $PdCl_2$(cod)/(*S*,*S*)-**5a**/$AgSbF_6$ catalytic system. The use of **8b** and **8c** dramatically increased the catalytic activity to afford the corresponding (*R*)-3-phenylcyclopentanone with an expected absolute configuration in 90% (85% ee, run 2) and 81% (30% ee, run 6) isolated yields, respectively. Quasi-equatorial

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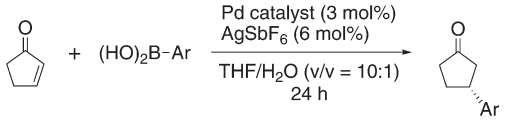
Table 4. Selected Bond Distances (Å) and Angles (deg) in 8c

Bond Distances			
Pd(1)−P(1)	2.230(1)	Pd(1)−Cl(1)	2.367(1)
Pd(1)−P(2)	2.237(1)	Pd(1)−Cl(2)	2.363(1)
Bond Angles			
P(1)−Pd(1)−P(2)	85.66(4)	C(14)−P(1)−C(15)	105.6(2)
P(1)−Pd(1)−Cl(2)	89.98(4)	C(15)−P(1)−C(1)	106.7(2)
Cl(2)−Pd(1)−Cl(1)	92.26(4)	C(2)−P(2)−Pd(1)	108.8(1)
Cl(1)−Pd(1)−P(2)	92.30(4)	C(21)−P(2)−Pd(1)	112.6(1)
C(1)−P(1)−Pd(1)	109.4(2)	C(21)−P(2)−C(3)	103.4(2)
C(14)−P(1)−Pd(1)	114.1(2)	C(3)−P(2)−C(2)	109.6(2)

Table 5. Asmmetric 1,4-Addition of Boronic Acids to 2-Cyclopentenone

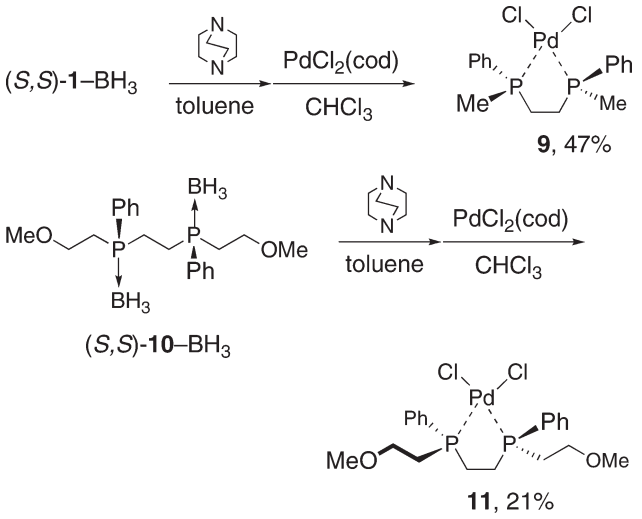


run	Ar	Pd catalyst	temp/°C	yield[a]/%	% ee[b]
1	Ph	$PdCl_2$(cod), (*S*,*S*)-**5a**	30	trace	
2	Ph	**8b**	30	90	85 (*R*)
3	Ph	**8b**	0	89	87 (*R*)
4	Ph	**8b**/AgOTf[c]	30	quant	83 (*R*)
5	Ph	**8b**/AgOTf[c]	0	36	92 (*R*)
6	Ph	**8c**	30	81	30 (*R*)
7	Ph	**9**	30	54	14 (*R*)
8	Ph	**11**	30	80	5 (*S*)
9	4-MeO-Ph	**8b**	30	94	82 (*R*)
10	4-CF_3-Ph	**8b**	30	91	72 (*R*)
11	4-Br-Ph	**8b**	30	95	78 (*R*)
12	2-Me-Ph	**8b**	30	94	72 (*R*)

[a] Isolated yield. [b] Enantiomeric excess was determined by HPLC with a Daicel Chiralcel OB-H column (0.46 cm × 25 cm × 2), using 2-propanol/hexane (v/v = 2:98) as an eluent column. [c] AgOTf (6 mol %) was used instead of $AgSbF_6$.

phenyl groups of **8b** blocked the open spaces of diagonal quadrants more effectively than the quasi-axial phenyl groups of **8c**, as shown in Figures 3 and 4, leading to a higher percent ee. AgOTf was also used as an additive, which provided (*R*)-3-phenylcyclopentanone quantitatively (83% ee at 30 °C, run 4) and in 36% yield (92% ee at 0 °C, run 5). Complexes **9** and **11** were prepared from (*S*,*S*)-**1**−BH_3 and (*S*,*S*)-**10**−BH_3, respectively (Scheme 6), and their catalytic performance was also examined. The 1,4-addition catalyzed by **9** proceeded to afford (*R*)-3-phenylcyclopentanone in 54% (14% ee, run 7) yield, while the reaction catalyzed by **11** yielded (*S*)-3-phenylcyclopentanone in 80% (5% ee, run 8). This suggests that the methoxyethyl (−CH_2CH_2OMe) arms substituted at the phosphorus atoms in **11** occupy the other open spaces and change the face selectivities of 2-cyclopentenone. The present catalytic system was also applied to the 1,4-addition of other arylboron reagents (runs 9−12); the corresponding 1,4-addition products

Scheme 6. Synthesis of Palladium Complexes 9 and 11



were obtained in high yields (91−95%) with good enantioselectivities (72−82% ee).

CONCLUSION

In summary, we have shown the practical synthesis of novel enantiomerically pure crown ether derivatives, i.e., (*S*,*S*)-15-diphosphacrown-5, (*S*,*S*)-18-diphosphacrown-6, (*R*,*R*)-18-diphosphacrown-6, and (*S*,*S*)-21-diphosphacrown-7, consisting of the P-stereogenic phosphine and ethyleneoxy units in the ring. These derivatives were prepared from P-stereogenic bisphosphine−boranes as key precursors; therefore, the obtained diphosphacrowns were also enantiomerically pure. The obtained P-stereogenic diphosphacrowns have a chiral ring structure as well as chiral heteroatoms (phosphorus atoms) that interact directly with guest ions and molecules. Their palladium(II) complexes were readily obtained and characterized by X-ray crystallography. The bisphosphine unit was chelate-coordinated to palladium(II) outside of the ring, and palladium(II) adopted the typical square-planar structure. Two phenyl groups substituted at chiral phosphorus atoms in the palladium complexes were located at two diagonal quadrants, which occupied quasi-equatorial and quasi-axial positions, respectively. We applied the P-stereogenic diphosphacrowns to the chiral ligand for the palladium-catalyzed asymmetric 1,4-addition of arylboronic acids to cyclopentenone. This reaction proceeded to afford the corresponding 1,4-addition products in high yield with good enantioselectivities. Further efforts are now being made to clarify the reaction intermediates as well as to design the P-stereogenic diphosphacrown ligand for enhancing the enantioselectivities; the results will be reported in the near future. The complexation of the P-stereogenic diphosphacrowns to various transition metals and their application to transition metal-catalyzed asymmetric reactions are also underway.

EXPERIMENTAL SECTION

Materials. THF and Et_2O were purchased and purified by passage through purification column under Ar pressure.[20] Dehydrated grade solvents of toluene and $CHCl_3$ were purchased and used without further purification. *N*,*N*,*N*′,*N*′-Tetramethylethylenediamine (TMEDA) and

(−)-sparteine were purchased and distilled from KOH under Ar atmosphere. 1,4-Diazabicyclo[2.2.2]octane (DABCO), *sec*-BuLi (1.0 M in cyclohexane and *n*-hexane solution), BH_3·THF (1.0 M in THF), $CuCl_2$, aqueous NH_3 (28%), NaH (60 wt % in mineral oil), diethylene glycol bis(*p*-toluenesulfonate) **4a**, triethylene glycol bis(*p*-toluenesulfonate) **4b**, tetraethylene glycol bis(*p*-toluenesulfonate) **4c**, $PdCl_2$(cod), $AgSbF_6$, and AgOTf were purchased and used without purification. 2-Cyclopentenone and all arylboronic acids were also purchased and used without purification. (*S*,*S*)-1,2-Bis(boranatophenylmethylphosphino)ethane (*S*,*S*)-**1**−BH_3 was prepared by the literature procedure[10a] with a minor modification.[10b] (*S*,*S*)-1,2-Bis[boranatophenyl(2-hydroxyethyl)phosphino]ethane (*S*,*S*)-**3**−BH_3 was prepared by the literature procedure[9] with a minor modification; the yield was improved by changing the molar ratio between *sec*-BuLi/TMEDA and (*S*,*S*)-**1**−BH_3. Dimethylphenylphosphine−borane **6**−BH_3 was prepared according to the literature procedure.[21] Although (*S*)-(2-hydroxyethyl)methylphenylphosphine−borane (*S*)-**7**−BH_3 was prepared by Ohashi, Imamoto, and co-workers,[12] herein we describe our synthetic procedure. Spectral data of all 1,4-addition products were matched with the literature values.[22] All reactions were performed under an Ar atmosphere, using standard Schlenk techniques.

Synthesis of (*S*,*S*)-3−BH_3. A solution of TMEDA (1.6 mL, 11 mmol) in THF (100 mL) was cooled to −78 °C under Ar atmosphere. To this stirred solution was added by syringe *sec*-BuLi (1.0 M in cyclohexane and *n*-hexane solution, 11 mL, 11 mmol). After 15 min, a solution of (*S*,*S*)-**1**−BH_3 (1.51 g, 5.0 mmol) in THF (50 mL) was added dropwise, and the mixture was stirred at −78 °C over 3 h. Dry CO_2 gas was bubbled through the reaction mixture, which was allowed to gradually warm to room temperature. After an additional 2 h of stirring at room temperature, the reaction mixture was acidified with 2 N HCl and extracted with EtOAc (3 × 100 mL). The organic layer was washed with brine and dried over $MgSO_4$. After filtration of $MgSO_4$, the solvent was dried in vacuo. To a stirred solution of (*S*,*S*)-**2**−BH_3 in THF (20 mL) was added BH_3·THF (1.0 M in THF, 30 mL, 30 mmol) at 0 °C under Ar atmosphere. The reaction mixture was stirred for 2 h at room temperature and poured into iced water. After extraction with EtOAc, the organic layer was washed with 2 N HCl and brine and dried over $MgSO_4$. $MgSO_4$ was removed by filtration, and the solvent was dried in vacuo. The residue was subjected to column chromatography on SiO_2 with hexane/EtOAc (v/v = 1:1) as an eluent to give (*S*,*S*)-**3**−BH_3 (1.00 g, 2.8 mmol, 55%) as a colorless solid: R_f 0.10 (hexane/EtOAc, v/v = 1:1); $[\alpha]^{22}_D$ +9.1 (*c* 1.0 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 0.73 (br q, J_{H-B} = 118.4 Hz, 6H), 1.89 (m, 2H), and 2.1−2.3 (m, 8H), 3.78 (m, 2H), 3.86 (m, 2H), 7.48 (t, *J* = 7.6 Hz, 4H), 7.52 (t, *J* = 7.6 Hz, 2H), 7.61 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 19.5 (d, J_{C-P} = 34.5 Hz), 29.1 (d, J_{C-P} = 35.3 Hz), 57.4, 126.8 (d, J_{C-P} = 52.8 Hz), 129.1 (m), 131.9, 132.0 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +14.7 (q, J_{P-B} = 54.8 Hz) ppm; HRMS (EI) calcd for $C_{18}H_{30}B_2O_2P_2$ $[M - H]^+$ 361.1829, found 361.1832. Anal. Calcd for $C_{18}H_{30}B_2O_2P_2$: C 59.72; H 8.35. Found: C 59.34; H 8.21.

Synthesis of (*S*,*S*)-5a-c−BH_3. A typical procedure is as follows. A solution of (*S*,*S*)-**3**−BH_3 (362 mg, 1.0 mmol) in THF (40 mL) was added to a suspension of NaH (120 mg, 3 mmol, 60 wt % in mineral oil; after washing with dry hexane at room temperature) at room temperature under Ar atmosphere. After being stirred for 30 min, the mixture was refluxed for 2 h and cooled to room temperature. A solution of diethylene glycol bis(*p*-toluenesulfonate) **4a** (415 mg, 1.0 mmol) in THF (10 mL) was added by a syringe, and the reaction mixture was stirred for 48 h at room temperature. H_2O (10 mL) was added to the reaction mixture, and extraction with EtOAc (3 × 50 mL) was carried out. The organic layer was dried over $MgSO_4$. $MgSO_4$ was removed by filtration, and the solvent was dried in vacuo. The residue was subjected to column chromatography on SiO_2 with hexane/EtOAc (v/v = 1:1) as an eluent to give (*S*,*S*)-**5a**−BH_3 (63 mg, 0.14 mmol, 14%) as a colorless solid.

(*S*,*S*)-5a−BH_3: R_f 0.30 (hexane/EtOAc, v/v = 1:1); $[\alpha]^{25}_D$ +103.0 (*c* 0.5 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 0.69 (br q, J_{H-B} = 127.7 Hz, 6H), 2.11 (m, 4H), 2.30 (m, 2H), 2.51 (m, 2H), 3.6−3.8 (m, 10H), 3.86 (m, 2H), 7.4−7.5 (m, 6H), 7.70 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 19.3 (d, J_{C-P} = 33.0 Hz), 27.0 (d, J_{C-P} = 34.8 Hz), 65.7, 70.3, 70.4, 127.8 (d, J_{C-P} = 54.6 Hz), 128.8, 131.4, 131.7 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +17.7 (br) ppm; HRMS (ESI) calcd for $C_{22}H_{36}O_3B_2P_2$ $[M + Na]^+$ 455.2223, found 455.2198. Anal. Calcd for $C_{22}H_{36}B_2O_4P_2$: C 61.15; H 8.40. Found: C 60.98; H 8.40.

(*S*,*S*)-5b−BH_3: 17% isolated yield; R_f 0.30 (hexane/EtOAc, v/v = 1:1); $[\alpha]^{25}_D$ +62.7 (*c* 1.0 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 0.69 (br q, J_{H-B} = 119.4 Hz, 6H), 2.14 (m, 4H), and 2.2−2.5 (m, 4H), 3.5−3.9 (m, 16H), 7.4−7.5 (m, 6H), 7.70 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 19.2 (d, J_{C-P} = 34.5 Hz), 26.5 (d, J_{C-P} = 34.5 Hz), 65.6, 70.4, 70.6, 70.8, 127.5 (d, J_{C-P} = 53.4 Hz), 128.9, 131.5, 131.9 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +16.5 (br) ppm; HRMS (EI) calcd for $C_{24}H_{40}B_2O_4P_2$ $[M]^+$ 476.2588, found 476.2588. Anal. Calcd for $C_{24}H_{40}B_2O_4P_2$: C 60.54; H 8.47. Found: C 60.76; H 8.47.

(*S*,*S*)-5c−BH_3: 20% isolated yield; R_f 0.1 (hexane/EtOAc: v/v = 1:2); $[\alpha]^{25}_D$ +50.2 (*c* 0.5 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 0.69 (br q, J_{H-B} = 96.1 Hz, 6H), 2.11 (m, 4H), and 2.30 (m, 4H), 3.5−3.8 (m, 20H), 7.4−7.5 (m, 6H), 7.70 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 19.3 (d, J_{C-P} = 33.9 Hz), 26.3 (d, J_{C-P} = 34.7 Hz), 65.5, 70.31, 70.34, 70.5, 70.8, 127.3 (d, J_{C-P} = 52.8 Hz), 128.8, 131.5, 131.8 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +16.3 (br) ppm; HRMS (ESI) calcd for $C_{26}H_{44}O_5B_2P_2$ $[M + Na]^+$ 543.2748, found 543.2740. Anal. Calcd for $C_{26}H_{44}O_5B_2P_2$: C 60.03; H 8.53. Found: C 59.76; H 8.35.

Synthesis of (*S*)-7−BH_3. A solution of (−)-sparteine (6.9 mL, 30 mmol) in Et_2O (150 mL) was cooled to −78 °C under Ar atmosphere. To this stirred solution was added by syringe *sec*-BuLi (1.0 M in cyclohexane and *n*-hexane solution, 30 mL, 30 mmol). After 15 min of stirring, a solution of dimethylphenylphosphine−borane **6**−BH_3 (3.8 g, 25 mmol) in Et_2O (40 mL) was added dropwise, and the mixture was stirred at −78 °C over 3 h. Dry CO_2 gas was bubbled through the reaction mixture, then it was allowed to gradually warm to room temperature. After an additional 2 h of stirring at room temperature, the reaction mixture was acidified with 2 N HCl and extracted with EtOAc (3 × 100 mL). The organic layer was washed with brine and dried over $MgSO_4$. After filtration of $MgSO_4$, the solvent was dried in vacuo. To the residue was added BH_3·THF (1.0 M in THF, 40 mL, 40 mmol) at 0 °C under Ar atmosphere. The reaction mixture was stirred for 2 h at room temperature and poured into iced water. After extraction with EtOAc, the organic layer was washed with 2 N HCl and brine and dried over $MgSO_4$. $MgSO_4$ was removed by filtration, and the solvent was dried in vacuo. The residue was subjected to column chromatography on SiO_2 with hexane/EtOAc (v/v = 3:1) as an eluent. Recrystallization from toluene and hexane (good and poor solvent, respectively) gave (*S*)-7−BH_3 (3.21 g, 17.6 mmol, 71%, 87% ee) as a colorless solid: R_f 0.40 (hexane/EtOAc: v/v = 1:1); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 0.78 (br q, J_{H-B} = 98.4 Hz, 3H), 2.07 (br, 1H), 2.18 (m, 2H), 3.86 (m, 2H), 7.50 (m, 3H), 7.75 (t, *J* = 8.1 Hz, 2H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 11.7 (d, J_{C-P} = 39.6 Hz), 30.8 (d, J_{C-P} = 35.5 Hz), 57.7, 129 (m), 131 (m) ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +4.4 (q, J_{P-B} = 63.0 Hz) ppm; HRMS (EI) calcd for $C_9H_{16}BOP$ $[M-H]^+$ 181.0954, found 181.0948.

Synthesis of (*R*,*R*)-3−BH_3. A solution of TMEDA (2.2 mL, 15 mmol) in THF (150 mL) was cooled to −78 °C under Ar atmosphere. To this stirred solution was slowly added by syringe *sec*-BuLi (1.0 M in cyclohexane and *n*-hexane solution, 15 mL, 15 mmol). After 15 min, a solution of (*S*)-7−BH_3 (1.09 g, 6.0 mmol) in THF (20 mL) was added dropwise, and the mixture was stirred at −78 °C over 3 h. $CuCl_2$ (1.21 g, 9.0 mmol) was added in one portion, and the mixture was allowed to slowly warm to room temperature. After 6 h, the reaction was quenched by the addition of 28% aqueous NH_3 (20 mL) and extracted with EtOAc (3 × 80 mL). The combined extracts were washed with 5% aqueous NH_3, 2 M HCl, and brine, and then dried over $MgSO_4$. After

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filtration of $MgSO_4$, the solvent was evaporated and dried in vacuo. The residue was subjected to column chromatography on SiO_2 with hexane/EtOAc (v/v = 1:1) as an eluent. The repeated recrystallization (three or four times) from toluene and hexane (good and poor solvent, respectively) gave optically pure (*R*,*R*)-**3**−BH_3 (0.39 g, 1.08 mmol, 36%, >99% ee) as a colorless solid: $[\alpha]^{25}_D$ −8.9 (*c* 1.0 in $CHCl_3$).

Synthesis of (*R*,*R*)-5b−BH_3. (*R*,*R*)-**5b**−BH_3 was obtained from (*R*,*R*)-**3**−BH_3 by the same procedure as (*S*,*S*)-**5b**−BH_3 in 22% isolated yield as a colorless solid: $[\alpha]^{18}_D$ −67.6 (*c* 1.0 in $CHCl_3$).

Synthesis of 8b and 8c. A typical procedure is as follows. A suspension of (*S*,*S*)-**5b**−BH_3 (95.2 mg, 0.20 mmol) and DABCO (224.4 mg, 2.0 mmol) in degassed toluene (10 mL) was heated to 55 °C under Ar atmosphere. After 13 h of stirring, the solvent was dried in vacuo. The residue was dissolved in degassed EtOAc (100 mL) and plugged through SiO_2 column under Ar atmosphere. The solvent was dried in vacuo, and the residue was dissolved in degassed $CHCl_3$. To this solution was added $PdCl_2$(cod) (68.5 mg, 0.24 mmol) in one portion. After the solution was stirred for 15 h at 55 °C under Ar atmosphere, the solvent was dried in vacuo. The residue was washed with toluene and hexane to give **8b** (85.9 mg, 0.14 mmol, 69%) as a colorless solid.

8b: $[\alpha]^{22}_D$ −122.6 (*c* 1.0 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 2.70−2.9 (m, 6H), 3.0−3.7 (m, 18H), 7.48 (m, 6H), 8.22 (t, *J* = 8.0 Hz, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 27.7−28.6 (m), 66.1, 70.0, 70.2, 70.9, 128.5−129.1 (m), 131.4, 133.4 (m) ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +72.1 ppm; HRMS (EI) calcd for $C_{24}H_{34}Cl_2O_4P_2Pd$ $[M - Cl]^+$ 589.0656, found 589.0656. Anal. Calcd for $C_{24}H_{34}Cl_2O_4P_2Pd$: C 46.06; H 5.48. Found: C 45.96; H 5.43.

8c: 74% isolated yield; $[\alpha]^{22}_D$ −110.0 (*c* 0.5 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 2.25 (m, 2H), 2.71 (m, 2H), 2.9−3.1 (m, 3H), 3.1−3.8 (m, 21H), 7.51 (m, 6H), 8.27 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 27.3 (d, *J* = 42.1 Hz), 29.9 (d, *J* = 33.1 Hz), 66.0, 69.6, 70.1, 70.6, 71.4, 126.1 (d, *J* = 50.5 Hz), 129.0, 131.7, 134.0 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +71.0 ppm; HRMS (ESI) calcd for $C_{26}H_{38}Cl_2O_5P_2Pd$ $[M - Cl]^+$ 633.0918, found 633.0922. Anal. Calcd for $C_{26}H_{38}Cl_2O_5P_2Pd$: C 46.62; H 5.72. Found: C 45.74; H 5.29.

Synthesis of (*S*,*S*)-10−BH_3. A solution of (*S*,*S*)-**3**−BH_3 (181 mg, 0.5 mmol) in THF (10 mL) was added to a suspension of NaH (80 mg, 2.0 mmol, 60 wt % in mineral oil; after washing with dry hexane at room temperature) at room temperature under Ar atmosphere. After the solution was stirred for 1.5 h at room temperature, MeI (150 μL, 2.5 mmol) was added by syringe, and the reaction mixture was stirred for 12 h at room temperature. HCl (aq) (1 N, 10 mL) was added to the reaction mixture, and extraction with EtOAc (3 × 50 mL) was carried out. The organic layer was dried over $MgSO_4$. $MgSO_4$ was removed by filtration, and the solvent was dried in vacuo. The residue was subjected to flash column chromatography on SiO_2 with hexane/EtOAc (v/v = 1:1) as an eluent to give (*S*,*S*)-**10**−BH_3 as a colorless solid quantitatively: R_f 0.5 (hexane/EtOAc: v/v = 1:1); $[\alpha]^{25}_D$ +31.5 (*c* 0.5 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 0.67 (br q, J_{H-B} = 115.8 Hz, 3H), 1.92 (m, 2H), 2.1−2.3 (m, 6H), 3.25 (s, 6H), 3.43 (m, 2H), 3.61 (m, 2H), 7.44 (t, *J* = 7.6 Hz, 4H), 7.51 (t, *J* = 7.6 Hz, 2H), 7.61 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 19.4 (d, J_{C-P} = 34.7 Hz), 26.5 (d, J_{C-P} = 35.5 Hz), 58.5, 66.8, 127.4, 128.9, 131.7, 131.9 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ +16.1 (m) ppm; HRMS (ESI) calcd for $C_{20}H_{34}O_2B_2P_2$ $[M - H]^+$ 389.2142, found 389.2144. Anal. Calcd for $C_{20}H_{34}O_2B_2P_2$: C 61.59; H 8.79. Found: C 61.42; H 8.54.

Synthesis of 9 and 11. Complexes **9** and **11** were obtained from (*S*,*S*)-**1**−BH_3 and (*S*,*S*)-**10**−BH_3 by the same procedure as **8b**, respectively.

9: 47% isolated yield as a colorless solid; ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 1.79 (m, 2H), 2.13 (d, J_{H-P} = 12.4 Hz, 6H), 2.42 (m, 2H), 2.54 (m, 2H), 7.5 (m, 6H), 8.0 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 14.7 (d, J_{C-P} = 34.7 Hz), 29.0 (d, J_{C-P} = 47.9 Hz), 127, 129.4, 132.4, 132.8 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ 60.8 ppm; HRMS (ESI) calcd for $C_{16}H_{20}Cl_2P_2Pd$ $[M + Na]^+$ 472.9350, found 472.9344. The specific rotation value of **9** could not be obtained because of its low solubility and the relatively small value.

11: 21% isolated yield as a colorless solid; $[\alpha]^{20}_D$ −83.7 (*c* 0.1 in $CHCl_3$); ^{1}H NMR ($CDCl_3$, 399.2 MHz) δ 2.2−2.6 (m, 6H), 2.73 (m, 2H), 2.96 (s, 6H), 3.62 (m, 2H), 4.08 (m, 2H), 7.50 (m 6H), 8.06 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 100.3 MHz) δ 27.6 (d, J_{C-P} = 45.4 Hz), 29.5 (d, J_{C-P} = 32.2 Hz), 58.5, 68.7, 128, 129.1, 131.9, 133.0 ppm; ^{31}P{^{1}H} NMR ($CDCl_3$, 161.5 MHz) δ 71.4 ppm; HRMS (ESI) calcd for $C_{20}H_{28}Cl_2O_2P_2Pd$ $[M + Na]^+$ 560.9874, found 560.9869.

General Procedure for the Pd-Catalyzed Aymmetric 1,4-Addition Reaction. A mixture of Pd catalyst (3 μmol), $AgSbF_6$ (6 μmol), and THF (0.25 mL) was placed in a flask under an Ar atmosphere. After the mixture was stirred at room temperature for 10 min, 2-cyclopentenone (8.4 μL, 0.10 mmol) and arylboronic acid (0.15 mmol) were added. Then degassed H_2O (0.05 mL) and THF (0.25 mL) were added. After being stirred for 24 h at 30 °C under Ar atmosphere, the reaction mixture was dried over Na_2SO_4. The solution was subjected to flash column chromatography on Al_2O_3 with CH_2Cl_2 as an eluent. The solvent was removed in vacuo, and the residue was subjected to preparative TLC on SiO_2 with hexane/EtOAc (v/v = 3:1) as an eluent to yield 3-arylcyclopentanone.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedure and spectral data for all new compounds and X-ray crystallographic data for (*S*,*S*)-**5a**−BH_3, (*S*,*S*)-**5b**−BH_3, **8b**, and **8c** and the corresponding CIF files. This material is available free of charge via the Internet at http://pubs.acs.org.

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