Synthesis of a Novel β-Cyclodextrin-Functionalized Diphosphine Ligand and Its Catalytic Properties for Asymmetric Hydrogenation

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The novel diphosphine ligand 6A,6B-bis(diphenylphosphino)-6A,6B-dideoxy-permethylated-β-cyclodextrin (6A,6B-PMCDP2) has been prepared by reacting 6A,6B-dimesyl-permethylated-β-cyclodextrin (or 6A,6B-bis(trifluoromethanesulfonyl)-permethylated-β-cyclodextrin) with $LiPPh_2$. A nine-bond P−P coupling of 10.2 Hz is observed for 6A,6B-PMCDP2. Treatment of 6A,6B-PMCDP2 with $PtCl_2$(COD) and $[Rh(COD)_2]BF_4$ in dichloromethane produced $PtCl_2$-(6A,6B-PMCDP2) and [Rh(COD)(6A,6B-PMCDP2)]BF_4, respectively. The rhodium complex [Rh(COD)(6A,6B-PMBCDP2)]BF_4 is catalytically active for hydrogenation of α-acetamidocinnamic acid, α-acetamidoacrylic acid, itaconic acid, and their methyl esters with optical yields up to 92% ee.

Introduction

Cyclodextrins (CDs) are bucket-shaped cyclic glucose oligomers with hollow hydrophobic cavities. One of the most interesting properties of cyclodextrins and their derivatives is that they have molecular recognition ability and can form inclusion complexes with selected organic and organometallic compounds.[1,2] To combine molecular recognition ability of cyclodextrin functionalities and catalytic activity of transition metal complexes, there have been considerable efforts in developing catalytic systems based on metal complexes attached to cyclodextrins.[1a,3,4] Impressive substrate selectivity[5,6] and regioselectivity[7] have recently been demonstrated with some of the reported metallocyclodextrins. Since cyclodextrins are chiral and cyclodextrin derivatives can recognize enantiomers of organic molecules,[8] one may expect that the cyclodextrin functionality could also induce stereoselectivity and that metallocyclodextrins are potentially useful as catalysts in asymmetric catalysis. However, this aspect has rarely been studied.[9]

In asymmetric catalysis with transition metal complexes, chiral bidentate phosphines are among the most popular ligands.[10] Phosphine or phosphinite ligands derived from monosaccharides[11,12] and the disaccharide trehalose[13,14] have also been exploited for asymmetric catalysis. Although several phosphine ligands attached to cyclodextrins have been synthesized[15] and some of them have been studied for hydrogenation[5] and hydroformylation[5,15c,d] of olefins, the uses of phosphine ligands attached to cyclodextrins in asymmetric catalysis have

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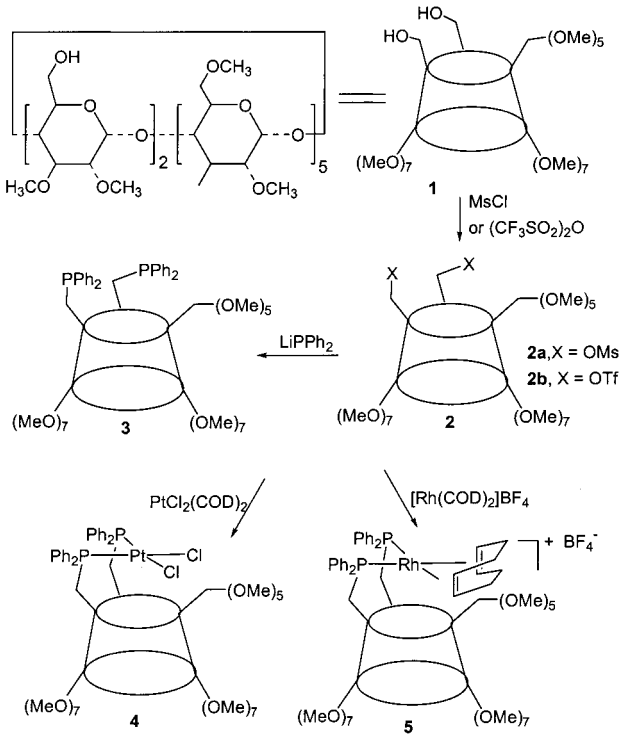
not been explored yet. The purpose of this paper is to report the synthesis and characterization of a novel diphosphine ligand derivatized from β-cyclodextrin and its rhodium and platinum complexes. The catalytic property of the rhodium complex for asymmetric hydrogenation of several prochiral olefins will also be described.

Results and Discussion

Synthesis of 6A,6B-PMCDP2. One of the most common methods to prepare phosphine ligands R_2PR' is to react appropriate R′X (X = halide, OTs, or OMs) with phosphides R_2PM (M = Li, Na, K) in tetrahydrofuran. Thus we have initially carried out the reaction of 6A,6B-dimesyl-permethylated-β-cyclodextrin (**2a**)[16] with $LiPPh_2$ in THF at room temperature. However, only a trace amount of the expected diphosphine ligand was produced under the reaction conditions and the reaction did not go completion even when the reaction mixture was refluxed for 3 days. It was subsequently found that the diphosphine ligand 6A,6B-PMCDP2 (**3**) can be prepared in high yield by reacting 6A,6B-dimesyl-permethylated-β-cyclodextrin with $LiPPh_2$ in a mixed solvent of DMF and THF at 80 °C for 18 h (Scheme 1). The ligand could also be prepared from the mild reaction of $LiPPh_2$ with 6A,6B-bis(trifluoromethanesulfonyl)-permethylated-β-cyclodextrin (**2b**), which was obtained from the reaction of 6A,6B-dihydroxyl-permethylated-β-cyclodextrin (**1**)[16] with $(CF_3SO_2)_2O$. The diphosphine ligand **3** is moderately air sensitive and can be purified by column chromatography on a silica gel column under an inert atmosphere.

Ligand **3** has been characterized by NMR, MS, and elemental analysis. In particular, the FAB-MS showed the expected molecular ion peak at *m*/*z* 1738, and the analytical data are consistent with the composition. The $^{31}P\{^1H\}$ NMR spectrum of **3** in CD_2Cl_2 displayed four lines at −23.20, −23.12, −21.49, and −21.41 ppm on a 300 MHz spectrometer. Because of the unsymmetrical

Scheme 1



nature of the molecule, the two PPh_2 groups of ligand **3** are not related by symmetry and are therefore magnetically nonequivalent. Thus two ^{31}P signals are expected for ligand **3**. There are two possible explanations for the appearance of the $^{31}P\{^1H\}$ NMR spectrum: (i) ligand **3** may exist in two isomers or (ii) the two nonequivalent phosphorus nuclei separated by nine bonds may couple to each other. 6A,6B-Disubstuted β-cyclodextrin derivatives such as 6A,6B-ditosyl-permethylated-β-cyclodextrin[16] and 6A,6B-*O*-bis[(p-allyloxy)phenyl)]-permethylated-β-cyclodextrin[17] are known to exist in two isomers in solutions. In one isomer, both the C6-substituents are outside of the cavity of β-cyclodextrin, while in the other isomer, one of the C6-substituents is included or partially included in the cavity of β-cyclodextrin. Considering the fact that 6A,6B-disubstuted β-cyclodextrin derivatives can exist in two isomers in solutions and that numerous examples of self-inclusion of C6-substituents in the cavity of β-cyclodextrin of C6-substituted cyclodextrins have been reported,[18] it seems reasonable to assume that similar isomerism may also occur for ligand **3**. If the four $^{31}P\{^1H\}$ lines in the ^{31}P NMR spectrum of ligand **3** are due to the existence of two isomers in solution due to inclusion of the PPh_2 groups, one might expect that the relative intensity of the four $^{31}P\{^1H\}$ lines would change with temperature or solvents, because the relative amounts of the two isomers are expected to change with temperature or solvents. In reality, the relative intensities of the four lines in the

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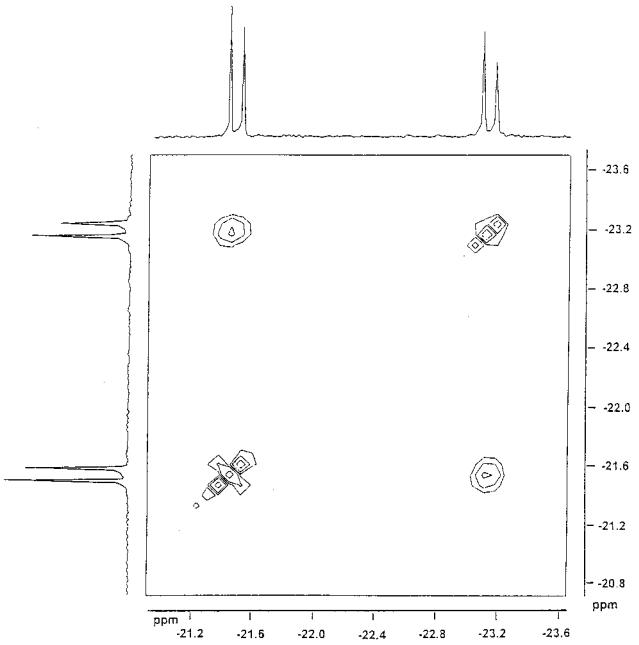

Figure 1. 2D homonuclear $^{31}P\{^1H\}$ COSY NMR spectrum of **3** in CD_2Cl_2.

$^{31}P\{^1H\}$ NMR spectra do not change appreciably when the temperature is changed from 193 to 353 K (in toluene-d_8) and when the solvent is changed from dichloromethane to chloroform, methanol, benzene, or toluene. Thus evidence for the existence of isomers of **3** could not be found. Thus the four $^{31}P\{^1H\}$ lines in the $^{31}P\{^1H\}$ NMR spectrum of ligand **3** are unlikely due to the existence of two isomers in solution, although the possibility of existence of isomers of **3** in solution could not be excluded.

On the other hand, we have found convincing evidence for coupling between the two phosphorus nuclei of **3** from a $^{31}P\{^1H\}-^{31}P\{^1H\}$ COSY experiment and from the $^{31}P\{^1H\}$ NMR spectra collected on spectrometers with different fields (300 and 400 MHz). The $^{31}P\{^1H\}-^{31}P\{^1H\}$ COSY spectrum of **3** shown in Figure 1 suggests that the two lines at −23.20 and −23.12 ppm are due to one PPh_2 group and the two lines at −21.49 and −21.41 ppm are due to the other PPh_2 group; the two PPh_2 groups couple to each other with a coupling constant of 10.2 Hz (in CD_2Cl_2). The coupling between the two PPh_2 groups is further supported by the $^{31}P\{^1H\}$ NMR spectra of **3** recorded on a 300 MHz and a 400 MHz NMR spectrometer, as the difference in the resonance frequencies of the $^{31}P\{^1H\}$ peaks due to each of the PPh_2 groups remains constant at different fields. The two PPh_2 groups of ligand **3** are separated by nine bonds. The observation of ^9J(PP) coupling between the two PPh_2 groups is quite unusual. To our knowledge, very few examples of P−P couplings for ^{31}P nuclei separated by more than seven bonds are known.[19] A ^7J(PP) of 4.8 Hz was observed for *Z*,*Z*-$Ph_2PCH_2C(t\text{-}Bu)$═N−N═$C(t\text{-}Bu)CH_2PPh_2$.[19a] A ^8J(PP) of 72.8 Hz was observed for the sterically congested phosphite ligand 2-{1-{3,5-bis(1,1-dimethylethyl)-2-{[2,4,8,10-tetrakis-(1,1-dimethylethyl)dibenzo[d,f][1,3,2]dioxaphosphepin-6-yl]oxy}phenyl}ethyl}-4,6-bis(1,1-dimethylethyl)phenyl diphenyl phosphite.[19b] A though-space coupling mechanism is thought to be operative for the observation of the ^8J(PP) in the congested compound.[19b,20] A ^9J(PP) of 4.0 Hz was observed for 2,6-bis(diethoxyphosphinoylmethyl)naphalene.[19c] Because of the torus-like structure of cyclodextrin, the two PPh_2 groups in **3** may be brought close to each other. Thus the two PPh_2 groups in **3** may also couple to each other via a through-space coupling mechanism. Unfortunately, we have not being able to get crystals of **3** suitable for X-ray diffraction to have a clear idea about the PP distance in **3**.

Synthesis of $PtCl_2$(6A,6B-PMCDP2) and [Rh(COD)(6A,6B-PMCDP2)]BF_4. In principle, the two phosphorus atoms of ligand **3** can bind to a metal center at two cis positions or two trans positions. To study the coordination property of ligand **3**, the reaction of ligand **3** with $PtCl_2$(COD) was carried out. Treatment of **3** with $PtCl_2$(COD) in dichloromethane produced the air-stable complex $PtCl_2$(6A,6B-PMCDP2) (**4**), which can be isolated as a pale yellow solid. The $^{31}P\{^1H\}$ NMR spectrum of **4** in $CDCl_3$ displayed two doublets at 13.9 and 4.4 ppm with ^2J(PP) = 14.6 Hz. The magnitude of the ^2J(PP) coupling constant indicates that the two PPh_2 groups are cis to each other. Consistent with the structure, the *J*(PtP) constants (3524.8 and 3657.2 Hz) are close to those observed for *cis*-$PtCl_2(PR_3)_2$.[21] For comparison, the *J*(PtP) constants for *trans*-$PtCl_2(PR_3)_2$ are usually less than 3000 Hz.[22] The structure of the closely related complex $PtCl_2$(6A,6B-$(NH_2)_2$CD) (6A,6B-$(NH_2)_2$CD = 6A,6B-diamino-6A,6B-dideoxy-β-cyclodextrin) has been confirmed by X-ray diffraction.[23] In $PtCl_2$(6A,6B-$(NH_2)_2$CD), the platinum atom is positioned on the top of the cavity of β-cyclodextrin. It is assumed that complex **4** has a similar conformation.

Reaction of ligand **3** with $[Rh(COD)_2]BF_4$ in dichloromethane produced the rhodium complex [Rh(COD)-(6A,6B-PMCDP2)]BF_4 (**5**), which can be isolated as an orange solid. Consistent with the proposed structure, the FAB-MS showed the ion peak of [Rh(COD)(6A,6B-PMCDP2)]$^+$ at *m*/*z* 1948; the $^{31}P\{^1H\}$ NMR spectrum in acetone-d_6 displayed two doublets of doublets at δ 18.6 ppm (dd, *J*(RhP) = 142.0 Hz, *J*(PP) = 31.6 Hz) and 13.7 ppm (dd, *J*(RhP) = 142.6 Hz, *J*(PP) = 31.6 Hz). As expected, the *J*(RhP) coupling constants are close to those observed for analogous complexes [Rh(COD)(PP)]$^+$ (PP = bidentate phosphines).[24]

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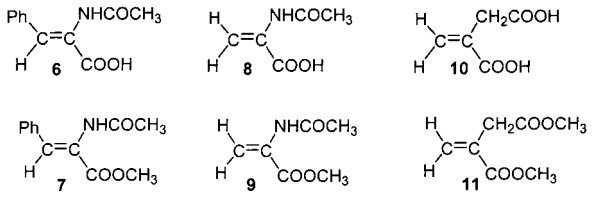
Chart 1



Hydrogenation Reactions. Many sugar-based bidentate phosphine and phosphinite ligands have been tested for asymmetric hydrogenation.[11−14] Excellent results have been obtained with some of the sugar-based bidentate phosphine and phosphinite ligands especially those with both of the phosphorus atoms attached to the same saccharide. To evaluate the catalytic properties of ligand **3** for asymmetric hydrogenation, hydrogenation of α-acetamidocinnamic acid (**6**), α-acetamidocinnamic methyl ester (**7**), α-acetamidoacrylic acid (**8**), α-acetamidoacrylic methyl ester (**9**), itaconic acid (**10**), and itaconic dimethyl ester (**11**) (see Chart 1 for their structures) was carried out using complex **5** as the catalyst. The catalytic reactions were performed under 1 atm of hydrogen at room temperature with the catalyst-to-substrate ratio of 1:100. After 24 h, all the substrates were quantitatively hydrogenated to give the corresponding hydrogenated products. The results are summarized in Table 1.

Hydrogenation of α-acetamidocinnamic acid (**6**) and α-acetamidocinnamic methyl ester (**7**) produced acetylphenylalanine (entries 1−3) and acetylphenylalanine methyl ester (entry 4), respectively. The major isomers of the hydrogenated products have an *R* configuration. The optical yields are moderate and are solvent dependent. Methanol appears to be the best solvent for stereoselectivity. In methanol, the optical yields for (*R*)-acetylphenylalanine and acetylphenylalanine methyl ester are 64% ee and 61% ee, respectively. Although the stereoselectivity is not as good as those with ligands such as DIOP,[25] DIPAMP,[26] and DUPHOS,[27] our experiments clearly demonstrated that the cyclodextrin moiety can induce stereoselectivity in hydrogenation.

Complex **5** also effected the hydrogenation of α-acetamidoacrylic acid (**8**) and α-acetamidoacrylic methyl ester (**9**) to give acetylalanine (entry 5) and acetylalanine methyl ester (entries 6−8), respectively. Again the major isomers of the hydrogenated products have an *R* configuration. In methanol, the optical yield for acetylalanine (60% ee) is comparable to that of acetylphenylalanine (64% ee). In the same solvent, the optical yield for acetylalanine methyl ester (78% ee) is significantly higher than that of acetylalanine (60% ee) and acetylphenylalanine methyl ester (61% ee). The optical yields for (*R*)-acetylalanine methyl ester with ligand **3** are lower than those obtained with ligands such as DUPHOS[27] and DIPAMP.[28] However, the optical yield of 78% ee for hydrogenation of **9** is higher than that obtained with DIOP[28] and is close to those obtained with BPPM[28] and PROPHOS.[28] It is noted that the stereoselectivity in the hydrogenation of α-acetamidoacrylates using trehalose-based diphosphine or diphosphinite ligands where the phosphorus atoms are attached to different glucose rings are generally low.[13c,14b] For example, the optical yield for hydrogenation of α-acetamidoacrylic methyl ester in MeOH (at room temperature) with the rhodium complex of methyl-protected 6,6′-bis(diphenylphosphino)-6,6′-dideoxy trehalose ligand is only 4% ee.[13c]

Table 1. Hydrogenation of Prochiral Olefins with [Rh(COD)(6A,6B-PMBCDP2)]BF_4

entry	substrate	solvent	% ee	configuration
1	**6**	MeOH	64	*R*
2	**6**	EtOH	49	*R*
3	**6**	acetone	51	*R*
4	**7**	MeOH	61	*R*
5	**8**	MeOH	60	*R*
6	**9**	MeOH	78	*R*
7	**9**	EtOH	73	*R*
8	**9**	CH_2Cl_2	64	*R*
9	**10**	MeOH	92	*S*
10	**10**	MeOH/Et_3N	92	*S*
11	**10**	EtOH	83	*S*
12	**10**	THF	76	*S*
13	**11**	EtOH	62	*S*

In the presence of complex **5**, itaconic methyl ester in EtOH was hydrogenated to give methylsuccinic methyl ester with *S* configuration predominant in an optical yield of 62% ee (entry 13). Under similar conditions, itaconic acid was hydrogenated to give methylsuccinic acid with *S* configuration predominant in an optical yield of 83% ee (entry 11). The optical yield of methylsuccinic acid is increased to 92% ee if the reaction was carried out in methanol (entry 9). Rhodium complexes with ligands such as DIOP,[25,29] DIPAMP,[26,30] and xylophos[11b] are known to induce higher stereoselectivity in the hydrogenation of α-acylaminoacrylic acids and their esters than in the hydrogenation of itaconic acid and its esters. Thus it is very interesting to note that the stereoselectivity for hydrogenation of itaconic acid is higher than that in the hydrogenation of α-acetamidocinnamic acid and α-acetamidoacrylic acid with complex **5**. Bidentate ligands that can induce high stereoselectivity are usually those that can form five-, six-, or seven-membered metallacylcles when complexed. Thus we are very pleased to note that rhodium complex with ligand **3** (which forms an 11-membered ring when complexed) can effect hydrogenation of itaconic acid with an optical yield up to 92% ee.

One may ask if a cyclodextrin moiety not linked to a catalytically active metal center could also effectively induce stereoselectivity in hydrogenation reactions. To test such a possibility, we have studied the hydrogenation of itaconic acid, itaconic dimethyl ester, α-acetamidocinnamic methyl ester, and α-acetamidocinnamic acid using [Rh(COD)(dppe)]BF_4 in the presence of permethylated *β*-cyclodextrin. It was found that the optical yields for these reactions are essentially zero. Thus the added permethylated *β*-cyclodextrin is rather ineffective in inducing stereoselectivity.

Cyclodextrin-functionalized porphyrin complexes have been previously tested for photocatalytic oxygenation of

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α-pinene to give α-pinene oxide with optical yields up to 67% ee.[9] Some cyclodextrin-modified phosphine ligands have been tested for hydrogenation[5] and hydroformylation[5,15c,d] of olefins. Our work appears to be the first example of asymmetric reduction of olefins with cyclodextrin-modified phosphine ligands.

Summary. We have successfully prepared a novel bidentate *β*-cyclodextrin-modified phosphine ligand and its rhodium and platinum complexes. We have demonstrated that the *β*-cyclodextrin-modified phosphine ligand can effect asymmetric hydrogenation of α-acetamidocinnamic acid, α-acetamidoacrylic acid, itaconic acid, and their methyl esters with optical yields up to 92% ee. We are now exploring the possibility of making use of the chiral ligand in other catalytic systems.

Experimental Section

Unless otherwise stated, all manipulations were carried out under an inert atmosphere using standard Schlenk techniques. Solvents were distilled under nitrogen from sodium-benzophenone (ether, THF) or calcium hydride (DMF, CH_2Cl_2). The starting material 6A,6B-dihydroxy-permethylated-*β*-cyclodextrin (**1**),[16] 6A,6B-dimesyl-permethylated-*β*-cyclodextrin (**2a**),[16] $[Rh(COD)_2]BF_4$,[31] and $[Rh(COD)(dppe)]BF_4$[32] were prepared according to literature methods. All other reagents were purchased from Aldrich Chemical Co. or Strem. ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectra were collected on a Bruker ARX-300 or a JEOL EX-400 spectrometer. ^1H and ^{13}C NMR chemical shifts are relative to TMS, and ^{31}P NMR chemical shifts are relative to 85% H_3PO_4. Mass spectra were collected on a Finnigan TSQ 7000 spectrometer. Microanalyses were performed by M-H-W Laboratories (Phoenix, AZ). Gas chromatographic determinations of optical yields of the hydrogenated products were performed on a HP-5890 GC/FID system equipped with a J&W Cyclosil B chiral GC column (30 m × 0.25 mm × 0.25 *μ*m). Optical rotations of the hydrogenated products were determined on a Perkin-Elmer 241 polarimeter using a Na lamp as the light source.

6A,6B-Bis(trifluoromethanesulfonyl)-permethylated-*β*-cyclodextrin (2b). To a dichloromethane solution (50 mL) of 6A,6B-dihydroxy-permethylated-*β*-cyclodextrin (2.0 g, 1.43 mmol) was added pyridine (116 *μ*L, 1.43 mmol). The reaction mixture was cooled to 0 °C, and then 552 *μ*L of trifluoromethanesulfonic anhydride was added dropwise. The mixture was stirred at 0 °C for 5 h, and then 50 mL of saturated $NaHCO_3$(aq) solution was added to the mixture. The organic layer was separated, and the aqueous layer was extracted with 3 × 30 mL of dichloromethane. The combined organic extracts were dried over anhydrous $MgSO_4$, filtered, and dried in vacuo. The crude product was purified by column chromatography on a silica gel column using 1:1 DCM/THF as the eluent to give a colorless solid (yield, 2.22 g, 93%). FAB-MS: *m*/*z* 1687 (M^+ + Na). ^1H NMR (300.13 MHz, CD_2Cl_2): *δ* 3.11−3.26 (m, 7 H), 3.29−4.09 (m, 92 H), 4.68−4.87 (m, 3 H, C*H*$_2$OTf, *CH*HOTf), 4.92−5.00 (m, 1 H, *CH**H***OTf), 5.00−5.23 (m, 7 H, H-1). $^{13}C\{^1H\}$ NMR (75.5 MHz, $CDCl_3$): *δ* 58.0−58.8 (m, OCH_3), 60.9−61.4 (m, OCH_3), 69.1−71.3 (m, C-5,6), 75.6(s, *C*H_2OTf), 75.7(s, *C*H_2OTf), 78.8−81.8 (m, C-2,3,4), 98.0−99.5 (m, C-1), 118.2 (q, J(FC) = 318.9 Hz, *C*F_3SO_3). $^{19}F\{^1H\}$ NMR (282.3 MHz, C_6D_6): *δ* −75.54, −75.57. Anal. Calcd for $C_{63}H_{106}O_{39}F_6S_2$: C, 45.43; H, 6.42. Found: C, 45.41; H, 6.43.

6A,6B-PMCDP2 (3). Method A. To a DMF (5 mL) solution of 6A,6B-dimesyl-permethylated-*β*-cyclodextrin (1.53 g, 0.982 mmol) was added a solution of $LiPPh_2$ dropwise in THF (0.5 M, 8 mL, 4 mmol; prepared by reacting $ClPPh_2$ with lithium metal in THF for 24 h) to give a pale orange solution. After 20 mL of THF was added, the reaction mixture was stirred at 80 °C for 18 h. The solvents were then pumped away under vacuum, and the residue was redissolved in THF. The solution was filtered through a pad of a mixture of silica gel and NH_4Cl. The filtrate was concentrated under vacuum. The crude product was washed with hexane to remove unreacted Ph_2PH. The residue was redissolved in dichlromethane and then purified by column chromatography on a silica gel column under N_2 using 30:1 $CHCl_3$/MeOH as the eluent to give a colorless solid (yield, 1.55 g, 91.0%).

Method B. To a THF (50 mL) solution of 6A,6B-bis-(trifluoromethanesulfonyl)-permethylated-*β*-cyclodextrin) (1.9 g, 1.14 mmol) cooled at 0 °C was added dropwise a solution of $LiPPh_2$ in THF (0.5 M, 8 mL, 4 mmol; prepared by reacting $ClPPh_2$ with lithium metal in THF for 24 h) to give a pale orange solution. The reaction mixture was stirred at 0 °C for 4 h. The pale orange color disappeared when 2 mL of BuCl was added. The solvent was then pumped away under vacuum, and the residue was washed with hexane to remove Ph_2PBu and Ph_2PH. The residue was redissolved in dichloromethane and concentrated and then purified by column chromatography on a silica gel column under N_2 using 30:1 $CHCl_3$/MeOH as the eluent to give a colorless solid (yield, 1.93 g, 97%). FAB-MS: *m*/*z* 1738 (M^+). ^1H NMR (300.13 MHz, CD_2Cl_2): *δ* 2.19−2.23 (m, 1 H), 2.55−2.63 (m, 2 H), 2.85−2.95 (m, 1 H), 3.00−4.30 (m, 95 H), 4.95−5.17 (m, 7 H, H-1), 7.19−7.77 (m, 20 H, PPh_2). $^{13}C\{^1H\}$ NMR (75.5 MHz, CD_2Cl_2): *δ* 31.4 (d, *J*(PH) = 14.7 Hz, *C*H_2PPh_2), 32.7 (d, *J*(PC) = 13.8 Hz, *C*H_2PPh_2), 58.5−59.6 (m, OCH_3), 61.4−62.1 (m, OCH_3,), 70.1−72.1 (m, C5, C-6), 80.7−84.6 (m, C-2,3,4), 98.1−100.1 (m, C1), 128.5−134.2 (m, Ph), 135.9−141.1 (m, *ipso*-Ph). $^{31}P\{^1H\}$ NMR (121.5 MHz, CD_2Cl_2): *δ* −23.16 (d, ^9J(PP) = 10.2 Hz), −21.45 (d, ^9J(PP) = 10.2 Hz). Anal. Calcd for $C_{85}H_{126}O_{33}P_2$: C, 58.75; H, 7.31. Found: C, 58.92; H, 7.12.

$PtCl_2$(6A,6B-PMCDP2) (4). A mixture of $PtCl_2$(COD) (19.8 mg, 0.053 mmol) and 6A,6B-PMCDP2 (100 mg, 0.058 mmol) in dichloromethane (5 mL) was stirred at room temperature for 24 h. The solvent was then pumped away under vacuum. The residue was washed with a 1:1 mixture of hexane and diethyl ether and dried to give a pale yellow solid. Yield: 100 mg, 94%. MS (FAB): *m*/*z* 1967 ([M − Cl]$^+$). ^1H NMR (300.13 MHz, acetone-d_6): *δ* 2.40−4.20 (m, 99 H), 4.70−5.70 (m, 7 H, H-1), 7.00−8.40 (m, 20 H, PPh_2). $^{31}P\{^1H\}$ NMR (121.5 MHz, $CDCl_3$): *δ* 13.9 (d with Pt satellites, *J*(PtP) = 3524.8 Hz, *J*(PP) = 14.6 Hz), 4.40 (d with Pt satellites, *J*(PtP) = 3657.2 Hz, *J*(PP) = 14.6 Hz). Anal. Calcd for $C_{85}H_{126}O_{33}P_2Cl_2Pt$: C, 50.95; H, 6.34. Found: C, 51.18; H, 6.34.

$[Rh(COD)(6A,6B\text{-}PMCDP2)]BF_4$ (5). A solution of $[Rh(COD)_2]BF_4$ (24 mg, 0.059 mmol) and 6A,6B-PMCDP2 (102 mg, 0.059 mmol) in dichloromethane (5 mL) was stirred at room temperature for 2 h. The solvent was then pumped away under vacuum. The residue was washed with a 1:1 mixture of hexane and diethyl ether and dried to give an orange solid. Yield: 108 mg, 90%. MS (FAB): *m*/*z* 1948 ([Rh(COD)(6A,6B-PMCDP2)]$^+$). ^1H NMR (300.13 MHz, acetone-d_6): *δ* 2.33−4.27 (m, 108 H), 4.44−4.79 (m, 3 H, olefinic H of COD), 5.06−5.66 (m, 7 H, H-1), 7.43−8.46 (m, 20 H, PPh_2). $^{31}P\{^1H\}$ NMR (121.5 MHz, acetone-d_6): *δ* 18.6 (dd, *J*(RhP) = 142.0 Hz, *J*(PP) = 31.6 Hz) and 13.7 (dd, *J*(RhP) = 142.6 Hz, *J*(PP) = 31.6 Hz. Anal. Calcd for $C_{93}H_{138}O_{33}P_2BF_4Rh$: C, 54.87; H, 6.83, P, 3.04. Found: C, 55.02; H, 6.72; P, 3.00.

Catalytic Hydrogenation. In a typical experiment, a solution (15 mL) of 1.95 mmol of substrate and 0.0195 mmol of complex **5** in a 250 mL Schlenk flask was stirred under nitrogen at room temperature for 15 min. The flask was then evacuated thoroughly and charged with H_2 at 1 atm. The reaction mixture was stirred at room temperature for 24 h. As indicated by ^1H NMR, the substrate has been completely hydrogenated under the reaction conditions.

The following procedures were used to isolate and characterize the hydrogenated products. For acetylphenylalanine, acetylalanine, and methylsuccinic acid, the solvent was removed after hydrogenation. The crude product was redissolved

in 25 mL of 1 M NaOH(aq) and washed with dichloromethane (2 × 20 mL). The aqueous layer was separated and neutralized with 1 M HCl to pH = 7. A saturated NaCl(aq) solution (20 mL) was added and then extracted with Et_2O (4 × 30 mL). The combined organic layers were dried over anhydrous $MgSO_4$, filtered and stripped on a rotavap, and dried under vacuum. The extent of conversion was measured by ^1H NMR spectroscopy. The enantiomeric excess was determined by chiral GC/FID after converting the acids into their methyl esters by treatment with trimethylsilyl diazomethane. The absolute configuration was assigned by comparison of the optical rotations of the product with the reported values ((*S*)-acetylphenylalanine, $[\alpha]^{25}_D$ 46.0° (*c* 1.0, EtOH);[33] (*R*)-acetylalanine, $[\alpha]^{25}_D$ 66.3° (*c* 2.0, H_2O);[33] and (*R*)-methylsuccinic acid, $[\alpha]^{25}_D$ 16.88° (*c* 2.16, EtOH)[33]). The ester products were purified by column chromatography on a silica gel column using 6:4 dichloromethane/EtOAc as the eluent. The enantiomeric excesses of the esters were determined by chiral GC/FID. The absolute configurations of the major optical isomers were assigned by comparison of the optical rotations of the products with the reported values ((*S*)-acetylphenylalanine ester $[\alpha]^{25}_D$ 15.9° (*c* 2.0, MeOH),[33] (*R*)-acetylalanine methyl ester ($[\alpha]^{25}_D$ −9.2 (*c* 1, $CHCl_3$))[34] and (*R*)-methylsuccinic dimethyl ester ($[\alpha]^{25}_D$ −17.01 (*c* 1, $CHCl_3$)[30]).

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