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# Chiral Palladium Template Promoted Asymmetric Hydrophosphination Reaction between Diphenylphosphine and Vinylphosphines

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An organopalladium complex containing ortho-metalated (*S*)-(1-(dimethylamino)ethyl)naphthalene as the chiral auxiliary has been used to promote the asymmetric hydrophosphination reactions between diphenylphosphine and (*E*)- or (*Z*)-diphenyl-1-propenylphosphine in high regio- and stereoselectivities under mild conditions. Hydrophosphination of (*Z*)-diphenyl-1-propenylphosphine with diphenylphosphine gave (*S*)-(–)-prophos as the major product. Using the same chiral metal template, the corresponding hydrophosphination reaction with (*E*)-diphenyl-1-propenylphosphine gave (*R*)-(+)-prophos predominantly. The hydrophosphination reactions generated the asymmetric diphosphines as bidentate chelates on the chiral naphthylamine palladium templates. The template products obtained undergo cis–trans isomerization in solution to form an equilibrium mixture of regioisomers. X-ray analysis of the major template products obtained from the hydrophosphination of (*Z*)-diphenyl-1-propenylphosphine reveals that the two regioisomers are cocrystallized in a 1:1 ratio. The naphthylamine auxiliary could be removed chemoselectively from the template products by treatment with concentrated hydrochloric acid to form the corresponding optically pure neutral complexes [(*R*)- or (*S*)-(prophos)$PdCl_2$]. Subsequently, the (*R*)- and (*S*)-dichloro complexes undergo ligand displacement with aqueous cyanide to generate the corresponding optically pure diphosphine ligands in high yields. Mechanistic pathways explaining the stereoselectivity of the chiral organopalladium template promoted hydrophosphination reactions are also proposed.

## Introduction

In terms of synthetic value and atom economy, the addition of phosphorus−hydrogen bonds to unsaturated compounds is an important reaction in organophosphorus chemistry.[1] Addition of the P−H moiety to carbon−carbon multiple bonds can proceed by thermal,[2] acidic,[3] basic,[4] or free radical[4d,5] pathways. However the use of lanthanide and transition metal complexes for such addition reactions often offer vast improvement in rate, selectivity, and stereocontrol.[6−14] Moreover, many functional groups can be incorpo-

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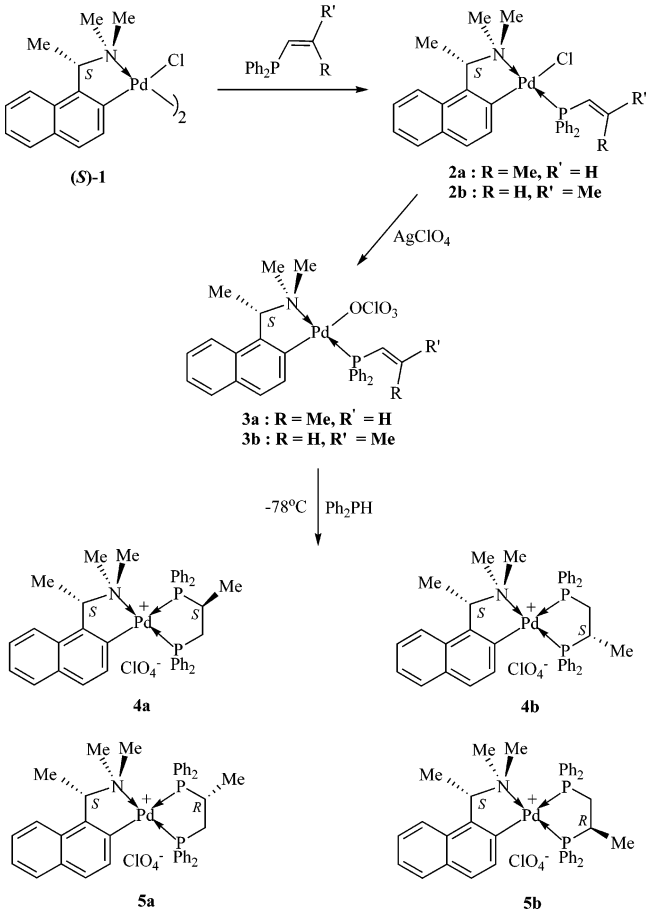
rated into the substrates without special protection as relatively mild reaction conditions are usually required in these metal-activated addition reactions. Transition metal catalyzed addition of P(V)−H bonds to alkynes, alkenes, allenes, and conjugated dienes using palladium, platinum, nickel, and rhodium complexes have been reported.[6−8] Similarly addition of P(III)−H bonds to carbon−carbon multiple bonds can be catalyzed by palladium, platinum, nickel, ruthenium, iridium, iron, and lanthanide complexes.[9−12] Apart from these catalytic processes, there are examples of hydrophosphination reactions which are promoted by stoichiometric quantities of transition metal complexes[11,13] and borane.[15] However, metal complex activated asymmetric addition of P−H moiety to carbon−carbon unsaturated compounds are relatively rare and are limited to the synthesis of chiral monophosphines with moderate stereoselectivities.[11,14]

Over the past few years, our group has reported the use of chiral cyclometalated−amine complexes as efficient chiral catalysts for asymmetric Claisen rearrangements,[16] reaction promoters for the oxidative coupling between vinylphosphines and imines,[17] chiral templates for asymmetric Diels−Alder reactions,[18] and asymmetric hydroamination reactions.[19] In pursing our interest in the application of chiral

**Scheme 1**




cyclometalated−amine complexes in asymmetric transformations, we hereby illustrate the efficiency of the chiral cyclopalladated−amine template promoted asymmetric hydrophosphination reactions for the synthesis of the important chiral diphosphine (*R*)- and (*S*)-prophos.[20]

## Results and Discussion

In the absence of a metal ion, diphenylphosphine shows no reactivity with (*E*)- or (*Z*)-diphenyl-1-propenylphosphine under ambient conditions. As illustrated in Scheme 1, the vinylphosphines were coordinated to (*S*)-**1** regioselectively to form the neutral complexes **2a**,**b**, which upon abstraction of the chloro ligands with silver perchlorate gave the perchlorato complexes, **3a**,**b** respectively.[21] Complexes **3a**,**b** were not isolated but were subsequently treated with $Ph_2PH$ at −78 °C to give the desired hydrophosphination products, **4** and **5**. The hydrophosphination reactions are highly regioselective, as the diphenylphosphino groups were added to the $\beta$-carbon of the vinylphosphines to form five-membered chelate rings exclusively. It is noteworthy that the chiral palladium complex (*S*)-**1** itself is not an efficient chiral template, as only trace amounts of the hydrophosphination products were formed under similar reaction condi-

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tions or at room temperature. The chloro ligand that is trans to the ortho-metalated aromatic carbon is known to be inert to ligand substitution by monodentate phosphines.[21,22] Thus, the occupation of one of the two essential coordination sites by the chloro ligand would hinder the simultaneous coordination of both reacting phosphorus substrates onto the metal template.

**Stereoselectivity: Hydrophosphination of (*Z*)-Diphenyl-1-propenylphosphine.** Complexes **4a**,**b** and **5a**,**b** are the four possible stereoisomeric products of the hydrophosphination reactions. Complexes **4a**,**b** are cis−trans regioisomers which adopt the same *S* absolute configuration at the newly generated stereogenic carbon centers within the diphosphine chelates but differ in the relative regio arrangement of the four nonequivalent donor atoms on the metal templates. Similarly, complexes **5a**,**b** are regioisomers with *R* absolute configuration at the new stereogenic centers. Hydrophosphination of ((*Z*)-propenylphosphine)palladium complex **3a** with $Ph_2PH$ gave three stereochemically distinct products. Prior to purification, the $^{31}P$ NMR spectrum in $CDCl_3$ exhibited three pairs of doublets in the ratio of 8:3:1. However, when the crude product mixture was kept at room temperature in dichloromethane for several days, an equilibrium mixture was formed in which the fourth stereoisomeric product was detected in the $^{31}P$ NMR spectrum, accompanied by a change in product ratio to 25:25:4:1, with the new stereoisomeric complex being the least abundant product. It is noteworthy that the ratio of the two major products had changed from 8:3 to 1:1.

Upon fractional crystallization, the two major isomers cocrystallized in equal quantities as yellow prisms from dichloromethane−diethyl ether in 64% yield, $[\alpha]_D$ +43° ($CH_2Cl_2$). A crystallographic analysis revealed that two regioisomers, **4a**,**b**, were indeed present in the same unit cell (Figure 1). Selected bond lengths and angles are listed in Table 1. As expected, the five-membered diphosphine chelates were formed in both regioisomers. Figure 1a shows the structure of **4a**, in which the newly formed stereogenic center at C(15) adopts the *S* absolute configuration. The five-membered diphosphine chelate adopts the $\delta$ ring conformation, with the methyl substituent at C(15) occupying the sterically favorable equatorial position.[23] In this molecule, however, the phenyl groups on P(1) and the neighboring N−Me groups on the organometallic ring are in an unfavorable pseudoeclipsed orientation. In addition, the naphthylene proton H(2) is also protruding toward the quasi-equatorial phenyl group on P(2). A serious tetrahedral distortion of 10.7° is observed in the square planar geometry at palladium (Figure 2). This geometrical adjustment is crucial in providing partial relief to the unfavorable interchelate steric repulsions. Figure 1b shows the structure of **4b**, in which the new stereogenic center at C(16A) adopts the same *S* absolute configuration. However the five-membered diphosphine chelate adopts the $\lambda$ ring conformation, with the methyl substituent at C(16A) occupying the sterically unfavorable axial position.[23] In this molecule, the unfavorable axial occupancy of the methyl group at C(16A) is somewhat compensated by relieving the interchelate steric interactions, as the phenyl groups on P(1A) and methyl groups on neighboring nitrogen adopt a staggered orientation. In addition, less steric repulsion exists between the naphthylene proton H(2A) and the quasi-axial phenyl group on P(2A). To accommodate the unfavorable 1,3-diaxial repulsion between the axial methyl substituent on C(16A) and the quasi-axial phenyl group on P(1A) in **4b**, a tetrahedral distortion of 7.6° was observed in the coordination geometry around palladium (Figure 2).

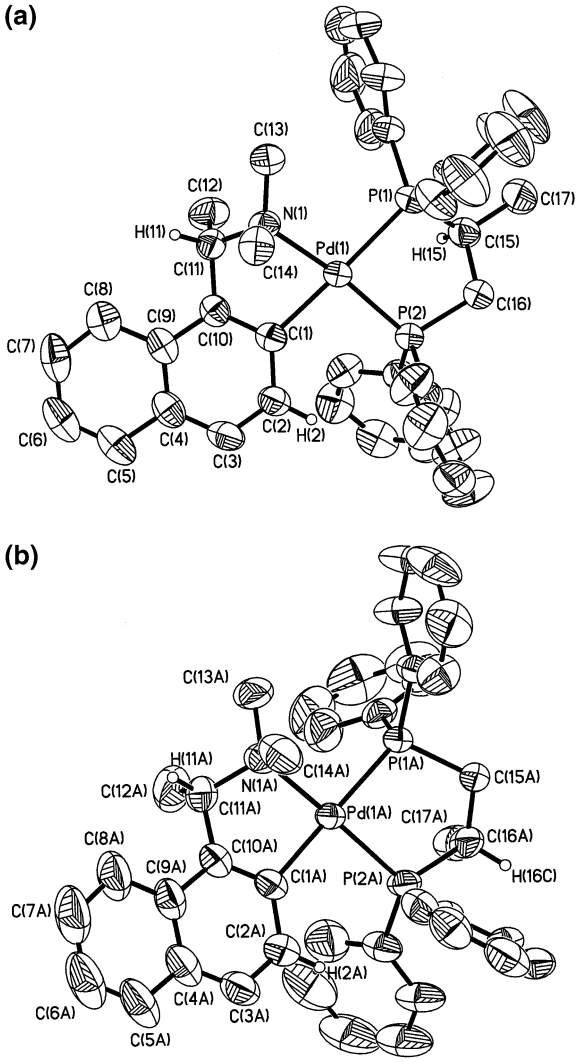


**Figure 1.** Molecular structure and absolute stereochemistry of the cationic complexes (a) **4a** and (b) **4b**.

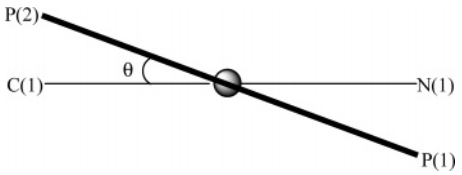


**Figure 2.** Tetrahedral distortion of complexes **4a**,**b** at the palladium(II) center. The distortion angle, $\theta$, of each complex is given in Table 1.

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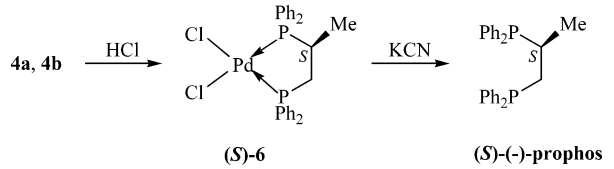
**Table 1.** Selected Bond Lengths (Å) and Angles (deg) for Complexes **4a**,**b**

| | molecule A, **4a** | molecule B, **4b** |
|---|---|---|
| Pd(1)−C(1) | 2.048(4) | 2.063(4) |
| Pd(1)−N(1) | 2.141(4) | 2.123(4) |
| Pd(1)−P(1) | 2.367(1) | 2.345(1) |
| Pd(1)−P(2) | 2.251(1) | 2.241(1) |
| P(1)−C(15) | 1.847(5) | 1.835(4) |
| P(2)−C(16) | 1.826(4) | 1.863(5) |
| C(15)−C(16) | 1.520(6) | 1.526(6) |
| C(15)−C(17) | 1.526(7) | |
| C(16)−C(17) | | 1.507(8) |
| C(1)−Pd(1)−P(1) | 171.0(1) | 178.9(1) |
| C(1)−Pd(1)−P(2) | 94.3(1) | 95.0(1) |
| C(1)−Pd(1)−N(1) | 79.8(2) | 80.6(2) |
| P(1)−Pd(1)−P(2) | 85.10(4) | 84.15(4) |
| N(1)−Pd(1)−P(1) | 101.6(1) | 100.4(1) |
| N(1)−Pd(1)−P(2) | 172.1(1) | 171.3(2) |
| Pd(1)−P(1)−C(15) | 103.0(2) | 106.4(1) |
| Pd(1)−P(2)−C(16) | 108.6(2) | 111.2(2) |
| P(1)−C(15)−C(16) | 106.6(3) | 109.5(3) |
| P(2)−C(16)−C(15) | 109.6(3) | 107.5(3) |
| P(1)−C(15)−C(17) | 117.6(4) | |
| P(2)−C(16)−C(17) | | 114.4(4) |
| C(17)−C(15)−C(16) | 113.9(4) | |
| C(17)−C(16)−C(15) | | 114.5(4) |
| tetrahedral distortion ($\theta$), deg | 10.7 | 7.6 |

The $^{31}$P NMR spectrum of the 1:1 mixture of **4a**,**b** in $CDCl_3$ exhibited two pairs of doublets at $\delta$ 46.9, 50.8 ($J_{PP}$ = 26.7 Hz) (for **4a**) and 39.9, 76.5 ($J_{PP}$ = 26.7 Hz) (for **4b**). Similiarly, the $^1$H NMR spectrum in $CDCl_3$ showed two sets of signals for the two regioisomers. Among these NMR signals, the proton resonances of the methine proton H(11) in the naphthylamine auxiliary and the methyl substituent at the newly formed stereogenic carbon of the diphosphine chelate were particularly informative for the NMR assignments of complexes **4a**,**b**. For each regioisomer, the resonance signal for the methine proton H(11) appeared as a quintet due to coupling with vicinal methyl protons and the phosphorus that is coordinated trans to the NMe group ($^3J_{HH}$ = $^4J_{PH}$),[24] while the methyl group at the stereogenic carbon center of the diphosphine chelate exhibited a doublet of doublet resonance signal due to coupling with both the vicinal methine proton and vicinal phosphorus atom. For complex **4b**, the $^1$H{$^{31}$P} decoupling experiments showed that the methine proton H(11) and the methyl protons of the diphosphine chelate coupled only to the P-atom resonating at $\delta$ 76.5. This showed that the P-atom resonating at $\delta$ 76.5 is clearly in the position vicinal to the protons of the methyl substituent at the newly formed stereogenic carbon center and is also coordinated trans to the NMe group. Therefore the $^{31}$P NMR signals at 39.9 and 76.5 ($J_{PP}$ = 26.7 Hz) can be unambiguously assigned to complex **4b**. For complex **4a**, the $^1$H{$^{31}$P} decoupling experiments showed that the methine proton H(11) coupled only to the P-atom resonating at $\delta$ 50.8. On the other hand, the methyl protons of the diphosphine chelate coupled only to the P-atom resonating at $\delta$ 46.9. Hence the P-atom resonating at $\delta$ 46.9 is geminal to the methyl group at the newly formed stereogenic carbon center and is also coordinated trans to the ortho-metalated aromatic carbon atom. Thus, the phosphorus resonances at $\delta$ 46.9 and 50.8 ($J_{PP}$ = 26.7 Hz) can be unambiguously assigned to isomer **4a**.

**Scheme 2**




Although the major hydrophosphination products are isolated as 1:1 isomeric mixture of two regioisomers, both the diphosphine chelates formed in **4a**,**b** adopt the same *S* absolute configuration at the newly generated chiral centers. Hence upon chemoselective removal of the naphthylamine auxiliary by treatment with concentrated hydrochloric acid, only the same dichloro palladium complex, (*S*)-**6**, was obtained from both **4a** and **4b** (Scheme 2). Optically pure dichloro complex (*S*)-**6** was obtained as pale yellow crystals from $CH_2Cl_2$−$Et_2O$ in 92% yield, $[\alpha]_D$ +71° ($CH_2Cl_2$). The $^{31}$P NMR spectrum of the dichloro complex in $CD_2Cl_2$ showed two singlets at $\delta$ 53.2 and 71.7, which is consistent with the literature values for its enantiomeric counterpart.[25] Further treatment of (*S*)-**6** with aqueous cyanide liberated the optically pure (*S*)-**(−)**-prophos[20] in 95% yield. The $^{31}$P NMR spectrum of the free diphosphine ligand in $CDCl_3$ exhibited two doublets at $\delta$ 1.7 and −20.6 ($^3J_{PP}$ = 21.0 Hz), which is in agreement with the reported values for its enantiomer.[25]

To establish the identities of the two minor products generated in the hydrophosphination reaction, the liberated optically pure (*S*)-(−)-prophos was recoordinated to the equally accessible (*R*)-**1**, and the resulting chloride counterion was replaced with a perchlorate anion by treatment with $AgClO_4$. As illustrated in Scheme 3, two regioisomers **7a**,**b** were generated from this simple metal complexation reaction. It is important to note that complexes **7a**,**b** are the enantiomeric forms of **5a**,**b**, respectively. In the absence of any chiral NMR solvent, the NMR spectra of enantiomers should reveal identical NMR resonance signals. By analyzing the $^{31}$P NMR spectra of the crude products obtained from the recomplexation process and those recorded directly from the hydrophosphination reaction, it is possible to determine if **5a**,**b** are indeed the two minor products of the hydrophosphination reaction. The $^{31}$P NMR spectrum of the crude recomplexation product mixture in $CDCl_3$ exhibited two pairs of doublets at $\delta$ 46.3, 50.9 ($J_{PP}$ = 34.3 Hz) and 30.4, 65.2 ($J_{PP}$ = 34.3 Hz) with the respective intensity ratio of ca. 4:1. Importantly, these phosphorus resonances for complexes **7a**,**b** were identical with those observed for the two minor products generated from the hydrophosphination reaction. Hence it could be confirmed that complexes **5a**,**b** were the two minor products of the hydrophosphination reaction. The $^{31}$P NMR

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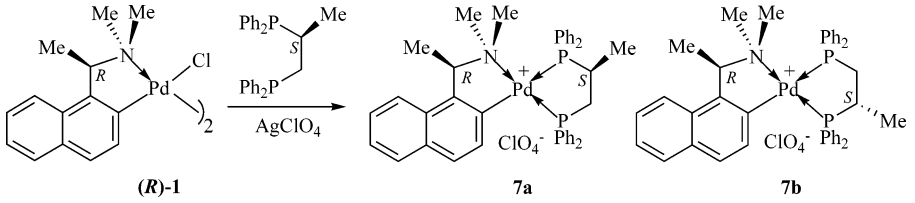
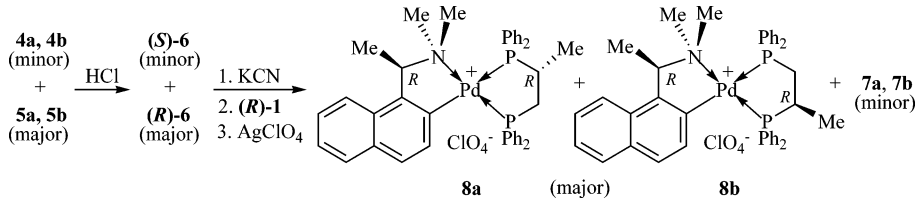
**Scheme 3**




**Scheme 4**




assignments for **5a**,**b** could be achieved by comparing the $^{31}$P NMR data with those of **4a**,**b**. It has been well established that, for a pair of regioisomers such as **5a**,**b** formed by an optically pure chiral diphosphine ligand on this class of organopalladium unit, the difference in $^{31}$P NMR chemical shifts would be significantly large.[21,26] On the other hand, for diastereomeric complexes such as **4a** and **5a**, which have the same regio arrangements but differ in the absolute configurations of the diphosphine chelate, the difference in $^{31}$P NMR chemical shifts would be relatively small.[21,26] Therefore the pair of doublet phosphorus resonances at $\delta$ 46.3 and 50.9 ($J_{PP}$ = 34.3 Hz) is assigned to **5a**, on the basis of the similarity of the chemical shifts to **4a**, while the pair of doublet phosphorus signals at $\delta$ 30.4 and 65.2 ($J_{PP}$ = 34.3 Hz) is assigned to **5b**.

With these spectroscopic assignments, the three stereoisomeric products generated from the hydrophosphination reaction between (*Z*)-propenylphosphine palladium complex **3a** and $Ph_2PH$ could be established to be complexes **4a**, **4b**, and **5a** in the ratio of 8:3:1. These three products subsequently undergo cis−trans isomerism to give the final equilibrium mixture of **4a**,**b** and **5a**,**b** in the ratio of 25:25:4:1. Similar cis−trans isomerization of unsymmetrical diphosphine chelate on the ortho-palladated naphthylamine complex has been reported previously.[26c]

**Stereoselectivity: Hydrophosphination of (*E*)-Diphenyl-1-propenylphosphine.** In principle, the hydrophosphination reaction between (*E*)-propenylphosphine palladium complex **3b** and $Ph_2PH$ may generate the same four possible stereoisomeric products, **4** and **5**, as that obtained from the reaction involving (*Z*)-isomer **3a**. The crude product mixture obtained from such hydrophosphination reaction of **3b** exhibited three pairs of doublets in the $^{31}$P NMR spectrum, indicating the formation of three distinct stereoisomeric products. By comparison with the $^{31}$P NMR data of previously identified complexes **4** and **5**, the three hydrophosphination products generated from complex **3b** were assigned to **4a**, **5a**, and **5b** with a ratio of 2:29:3, respectively. Similarly, when this crude product mixture was kept at room temperature in $CH_2Cl_2$ for several days, the fourth product, identified to be **4b**, was detected and the equilibrium ratio of the four hydrophosphination products **4a**, **4b**, **5a**, and **5b** was 1:1:25:7, respectively. Apparently, **4a** and **5a** undergo cis−trans isomerization to give **4b** and **5b**, respectively, until an equilibrium between the corresponding cis−trans isomers was achieved. It is noteworthy that the absolute configurations of the chiral carbon centers within the bidentate chelates remain unchanged during the ligand rearrangement process.

The crude isomeric products, however, could not be purified by fractional crystallization or column chromatography. Treatment of the crude isomers with concentrated HCl removed the naphthylamine auxiliary chemoselectively to afford an enantiomeric mixture of dichloropalladium complexes (*R*)-**6** and (*S*)-**6** in 82% yield (Scheme 4). Despite the fact that the enantiomer (*R*)-**6** is in large excess (16:1), the dichloro complex could not be isolated in its enantiomerically pure state, even after repeated crystallizations. Thus, the enantiomerically enriched dichloropalladium complexes were treated with aqueous cyanide to liberate the enantiomeric free diphosphine ligands, which were subsequently recoordinated to (*R*)-**1**, to form to the more crystalline complexes, **8a**,**b**, with a small amount of **7a**,**b** as minor impurities (Scheme 4). It is important to note that complexes **8a**,**b** are the enantiomers of the fully characterized **4a**,**b**, respectively. Upon fractional crystallization, an expected 1:1 mixture of **8a**,**b** was obtained from $CH_2Cl_2$−$Et_2O$ as yellow crystals in 68% yield, $[\alpha]_D$ −43° ($CH_2Cl_2$). Similarly the treatment of **8a**,**b** with concentrated HCl, followed by ligand displacement with aqueous cyanide, gave the optically pure diphosphine (*R*)-(+)-prophos.[20,25]

**Mechanistic Considerations.** Metal-promoted hydrophosphination of alkenes usually involves the following steps:[9a,b,d,11,12c,13b,c,e,27] first, oxidative addition of the P−H moiety to the metal ion to form M−H and M−P bonds or protonolysis of P−H bond to give M−P phosphido complex; second, insertion of alkene into the M−H or M−P bonds or, alternatively, the nucleophilic phosphido complex un-

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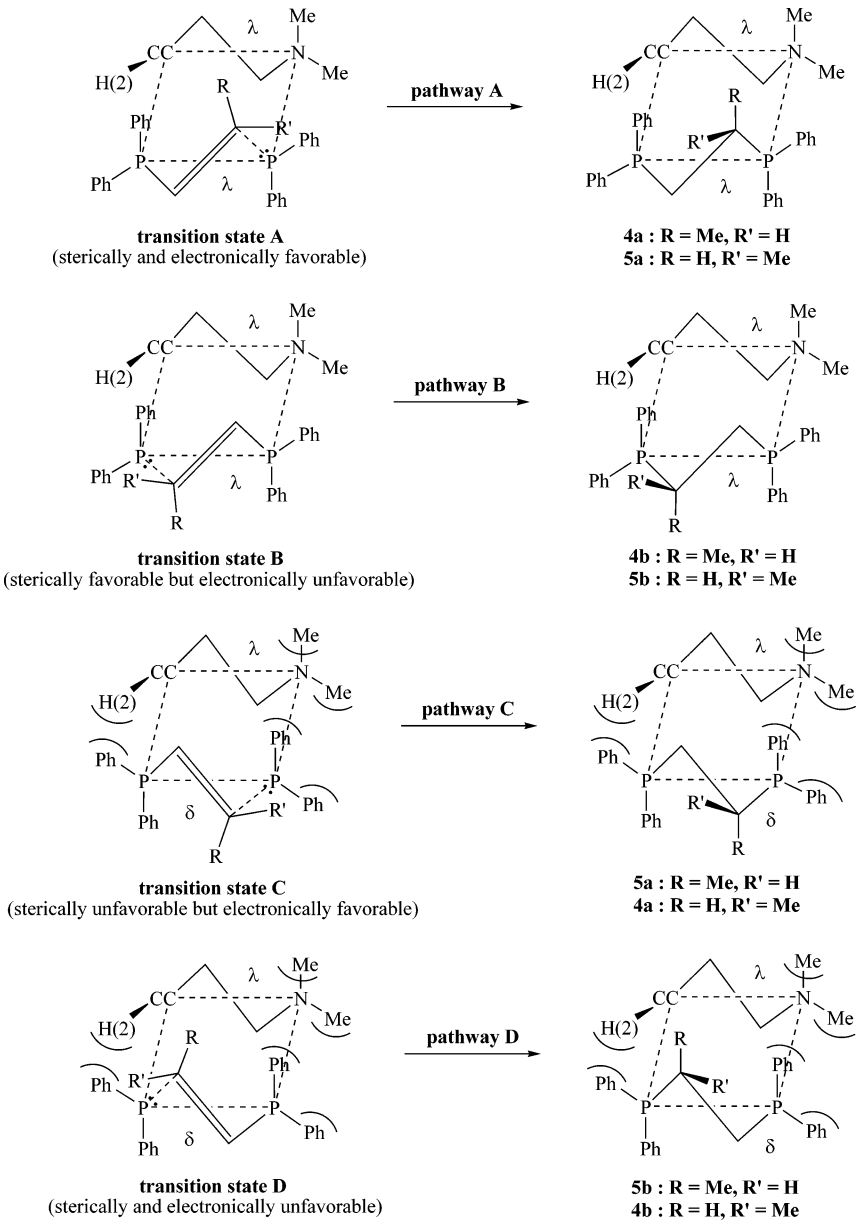
(27) Douglass, M. R.; Stern, C. L.; Marks, T. J. *J. Am. Chem. Soc.* **2001**, *123*, 10221.

**Scheme 5**




dergoes nucleophilic (Michael) addition to alkene; finally, reductive elimination or protonolysis to give the products. It has been reported that, upon coordination of secondary phosphines to palladium or platinum, the P−H proton is relatively acidic and can undergo proton exchange with the solvents.[13e,28] In the absence of external base, a small amount of nucleophilic phosphido complex can be generated, which subsequently undergoes nucleophilic addition to diphenylvinylphosphine.[13e] We believe that the current chiral metal template promoted hydrophosphination reactions involve a similar nucleophilic addition pathway, in which the generation of the phosphido complex is followed by intramolecular Michael addition to coordinated vinylphosphine and subsequent protonolysis to give the products.

Interestingly, for hydrophosphination of (*Z*)-isomer **3a**, the major products formed are **4a**,**b**, in which the new chiral carbon centers adopt the same *S* absolute configuration (total *R*:*S* selectivity is ca. 1:10, respectively). On the other hand, hydrophosphination of the (*E*)-isomer **3b** gives predominantly **5a**,**b**, which adopt the same *R* absolute configuration at the new chiral carbon centers (total *R*:*S* selectivity is 16:1, respectively). It is noteworthy that the addition of external weak base such as triethylamine resulted in formation of the same hydrophosphination products with similar stereoselectivity. On the other hand the use of strong base such as butyllithium gave the hydrophosphination products, with lower stereoselectivity, after an additional protonation step.

The high stereoselectivity observed from the hydrophosphination of **3a**,**b** can be explained by consideration of the possible reaction pathways. In principle, the stereoselective nucleophilic addition step may proceed via four different pathways as illustrated in Scheme 5. Of the four possible pathways, A and B are sterically more favorable as they involve transition states in which severe interchelate repul-

(28) Bartsch, R.; Hietkamp, S.; Morton, S.; Peters, H.; Stelzer, O. *Inorg. Chem.* **1983**, *22*, 3624.

sions between the chiral auxiliary and reacting phosphorus substrates are absent.[29] With pathway A, the (*Z*)-isomer **3a** would generate complex **4a**, in which the new stereogenic carbon center adopts the *S* absolute configuration but the ring conformation of the five-membered diphosphine chelate may not be rigid. On the other hand, the (*E*)-isomer **3b** with the same pathway would generate complex **5a** with *R* absolute configuration at the new chiral carbon center.

Interestingly, pathways A and B would generate diphosphine chelate complexes with the same absolute configuration at the new stereogenic carbon centers, except that the two nonequivalent phosphorus donors are disposed in different regio-orientations. The interchelate steric interactions of the two transition states in both pathways are similar. Thus, comparable amounts of **4a**,**b** would be expected from the hydrophosphination of complex **3a**. However, an 8:3 mixture of complexes **4a**,**b** was obtained as the kinetic products, respectively. The preferred formation of **4a** to **4b** must be due to the electronic preferences of transition state A to B. In transition state A, the $\pi$-accepting vinylphosphine is coordinated in the position trans to the $\sigma$-donating NMe group, while the electron-rich phosphido moiety is located trans to the strong $\pi$-accepting ortho-metalated carbon atom. In contrast, in transition state B, the two strong $\pi$-accepting donors are located in the trans positions. Thus electronically, transition state A is more stable than transition state B. Once the diphosphine chelate was formed, the two tertiary phosphorus donors become electronically comparable, and a 1:1 equilibrium mixture of **4a**,**b** was obtained as a result of the cis−trans isomerism. Similarly, the hydrophosphination reaction of **3b** gave a 29:3 mixture of **5a**,**b** as the kinetic products but equilibrate to a 25:7 mixture of the two stereoisomers upon cis−trans isomerism. Both the remaining pathways, C and D are unfavorable as they involve transition states in which severe interchelate repulsions exist between the chiral auxiliary and reacting phosphorus substrates.[29]

In conclusion, the synthesis of chiral diphosphine via chiral organopalladium template promoted asymmetric hydrophosphination has been demonstrated. The hydrophosphination reactions proceed with high regio- and stereoselectivities under mild conditions. Further investigations on the synthesis of P-stereogenic diphosphines with selected functionalities are currently in progress.

## Experimental Section

Reactions involving air-sensitive compounds were performed under a positive pressure of purified nitrogen. NMR spectra were recorded at 25 °C on Bruker ACF 300 and AMX500 spectrometers. Optical rotations were measured on the specified solution in a 0.1-dm cell at 25 °C with a Perkin-Elmer model 341 polarimeter. Elementary analyses were performed by the Elemental Analysis Laboratory of the Department of Chemistry at the National University of Singapore.

The enantiomerically pure forms of (*S*)-**1** and (*R*)-**1**[24a,30] were prepared according to standard literature methods. Complexes **2** and **3** were prepared as previously reported by our group.[21]

**Caution!** *All perchlorate salts should be handled as potentially explosive compounds.*

**Hydrophosphination of [*SP*-4-3-(*S*)-{1-[1-(Dimethylamino)ethyl]naphthyl-$C^2$,$N$}perchlorato{(*Z*)-diphenyl-1-propenylphosphine-$P$}]palladium(II), 3a.** Complex 2a (0.308 g) in $CH_2Cl_2$ (30 mL) and aqueous $AgClO_4$ (0.150 g) were stirred vigorously at room temperature for 2 h. The mixture was filtered through Celite (to remove AgCl), washed with water (3 × 30 mL), and dried ($MgSO_4$). The mixture was then degassed and treated with $Ph_2PH$ (0.102 g) at −78 °C for 16 h. The crude product was recrystallized from $CH_2Cl_2$−$Et_2O$ to give the 1:1 mixture of 4a,b as yellow prisms: mp 235−236 °C (dec); $[\alpha]_D$ +43° (*c* 0.8, $CH_2Cl_2$); 0.283 g (64% yield). Anal. Calcd for $C_{41}H_{42}ClNO_4P_2Pd$: C, 60.3; H, 5.2; N, 1.7. Found: C, 60.5; H, 5.3; N, 1.8. Spectroscopic assignments follow. [*SP*-4−{(*S*)-1-[1-(dimethylamino)ethyl]naphthyl-$C^2$,$N$}{(*S*)-1,2-bis(diphenylphosphino)propane-$P^1$,$P^2$}]palladium(II) perchlorate, 4a: $^{31}$P NMR ($CDCl_3$) $\delta$ 46.9 (d, 1P, $J_{PP}$ = 26.7 Hz, $P^2$), 50.8 (d, 1P, $J_{PP}$ = 26.7 Hz, $P^1$); $^1$H NMR ($CDCl_3$) $\delta$ 1.15 (dd, 3H, $^3J_{PH}$ = 11.6 Hz, $^3J_{HH}$ = 6.8 Hz, P$^2$CH*Me*), 1.73 (d, 3H, $^3J_{HH}$ = 6.0 Hz, CH*Me*), 2.12−2.23 (m, 1H, P$^1$C*H*H′), 2.34 (dd, 3H, $^4J_{PH}$ = 3.9 Hz, $^4J_{P'H}$ = 3.3 Hz, N$Me_{eq}$), 2.55−2.64 (m, 1H, P$^1$CH*H*′), 2.77−2.93 (m, 1H, P$^2$C*H*Me), 2.86 (d, 3H, $^4J_{PH}$ = 1.2 Hz, N$Me_{ax}$), 4.46 (qn, 1H, $^3J_{HH}$ = $^4J_{PH}$ = 6.0 Hz, C*H*Me), 6.73−8.08 (m, 26H, aromatics). [*SP*-4-3-{(*S*)-1-[1-(dimethylamino)ethyl]naphthyl-$C^2$,$N$}-{(*S*)-1,2-bis(diphenylphosphino)propane-$P^1$,$P^2$}]palladium(II) perchlorate, 4b: $^{31}$P NMR ($CDCl_3$) $\delta$ 39.9 (d, 1P, $J_{PP}$ = 26.7 Hz, $P^1$), 76.5 (d, 1P, $J_{PP}$ = 26.7 Hz, $P^2$); $^1$H NMR ($CDCl_3$) $\delta$ 0.73 (dd, 3H, $^3J_{PH}$ = 16.6 Hz, $^3J_{HH}$ = 7.4 Hz, P$^2$CH*Me*), 2.11 (d, 3H, $^3J_{HH}$ = 6.0 Hz, CH*Me*), 2.22−2.31 (m, 1H, P$^1$C*H*H′), 2.46 (d, 3H, $^4J_{PH}$ = 1.2 Hz, N$Me_{ax}$), 2.64−2.79 (m, 1H, P$^1$CH*H*′), 2.73 (dd, 3H, $^4J_{PH}$ = 3.3 Hz, $^4J_{P'H}$ = 2.7 Hz, N$Me_{eq}$), 3.24−3.52 (m, 1H, P$^2$C*H*Me), 4.58 (qn, 1H, $^3J_{HH}$ = $^4J_{PH}$ = 6.0 Hz, C*H*Me), 6.81−8.43 (m, 26H, aromatics).

**Synthesis of [*SP*-4-3-(*S*)-Dichloro{1,2-bis(diphenylphosphino)propane-$P^1$,$P^2$}]palladium(II), (*S*)-6.** Concentrated HCl (10 mL) was added to a solution of **4a**,**b** (0.180 g) in $CH_2Cl_2$ (25 mL). The reaction mixture was stirred vigorously at room temperature for 16 h, washed with water (3 × 20 mL), and dried ($MgSO_4$). Crystallization of the crude product from $CH_2Cl_2$−$Et_2O$ gave the dichloro complex as pale yellow crystals: $[\alpha]_D$ +71° (*c* 0.5, $CH_2Cl_2$); 0.120 g (92% yield); $^{31}$P NMR ($CD_2Cl_2$) $\delta$ 53.2 (s, 1P, $P^1$), 71.7 (s, 1P, $P^2$); $^1$H NMR ($CD_2Cl_2$) $\delta$ 1.06 (dd, 3H, $^3J_{PH}$ = 13.7 Hz, $^3J_{HH}$ = 6.8 Hz, P$^2$CH*Me*), 2.16−2.37 (m, 1H, P$^1$C*H*H′), 2.44−2.73 (m, 1H, P$^1$CH*H*′), 2.76−2.96 (m, 1H, P$^2$C*H*Me), 7.46−7.98 (m, 20H, aromatics). Other physical properties are consistent with those reported previously for its enantiomer.[25]

**Liberation of (*S*)-1,2-Bis(diphenylphosphino)propane, (*S*)-(−)-prophos.** A solution of (*S*)-**6** (0.060 g) in $CH_2Cl_2$ (25 mL) was stirred vigorously with a saturated aqueous solution of KCN (2 g) for 2 h. The organic layer was separated, washed with water (3 × 20 mL), and dried ($MgSO_4$). Upon removal of solvent, a white solid was obtained: 0.040 g (95% yield); $^{31}$P NMR ($CDCl_3$) $\delta$ 1.7 (d, 1P, $^3J_{PP}$ = 21.0 Hz, *P*), −20.6 (d, 1P, $^3J_{PP}$ = 21.0 Hz, *P*); $^1$H NMR ($CDCl_3$) $\delta$ 1.28 (dd, 3H, $^3J_{PH}$ = 15.7 Hz, $^3J_{HH}$ = 6.8 Hz, CH*Me*), 1.81−1.94 (m, 1H, C*H*H′), 2.23−2.38 (m, 2H, CH*H*′, C*H*Me), 7.21−7.41 (m, 20H, aromatics). Other physical properties are consistent with those reported previously.[20]

**Hydrophosphination of [*SP*-4-3-(*S*)-{1-[1-(Dimethylamino)ethyl]naphthyl-$C^2$,$N$}perchlorato{(*E*)-diphenyl-1-propenylphosphine-$P$}]palladium(II), 3b.** The hydrophosphination reaction was performed similarly using complex 3b as the starting material. The crude product was treated directly with concentrated HCl, and the enantiomerically enriched neutral dichloropalladium complexes

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**Table 2.** Crystallographic Data for Complexes **4a**,**b**

| | |
|---|---|
| formula | $C_{41}H_{42}ClNO_4P_2Pd$ |
| fw | 816.55 |
| space group | *P*1 |
| cryst system | triclinic |
| *a*/Å | 9.7391(3) |
| *b*/Å | 11.4002(4) |
| *c*/Å | 17.9819(6) |
| α/deg | 82.907(1) |
| *β*/deg | 80.118(1) |
| *γ*/deg | 77.767(1) |
| *V*/Å$^3$ | 1914.3(1) |
| *Z* | 2 |
| *T*/K | 295(2) |
| $\rho_{calcd}$/g cm$^{-3}$ | 1.417 |
| *λ*/Å | 0.710 73 (Mo) |
| $\mu$/cm$^{-1}$ | 6.80 |
| Flack params | 0.00(2) |
| R1 (obsd data)[a] | 0.0456 |
| wR2 (obsd data)[b] | 0.1063 |

[a] $R1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. [b] $wR2 = \sqrt{\{\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]\}}$, $w^{-1} = \sigma^2(F_o^2) + (aP)^2 + bP$.

(*R*)-6 and (*S*)-6 were crystallized from $CH_2Cl_2-Et_2O$ as yellow crystals in 82% yield.

**Synthesis of [*SP*-4-4-{(*R*)-1-[1-(Dimethylamino)ethyl]naphthyl-*C*$^2$,*N*}{(*R*)-1,2-bis(diphenylphosphino)propane-*P*$^1$,*P*$^2$}]-palladium(II) Perchlorate, 8a, and [*SP*-4-3-{(*R*)-1-[1-(Dimethylamino)ethyl]naphthyl-*C*$^2$,*N*}{(*R*)-1,2-bis(diphenylphosphino)propane-*P*$^1$,*P*$^2$}]palladium(II) Perchlorate, 8b.** Enantiomerically enriched dichloropalladium complexes (*R*)-6 and (*S*)-6 (0.287 g) were dissolved in $CH_2Cl_2$ (30 mL), and the solution was stirred vigorously with a saturated aqueous solution of KCN (2 g) for 2 h. The organic layer was separated, washed with water (3 × 20 mL), and dried ($MgSO_4$). After that it was added to a solution of (*R*)-1 (0.177 g) in $CH_2Cl_2$ (10 mL), followed by addition of aqueous $AgClO_4$ (0.140 g). The mixture was stirred vigorously for 2 h. Then it was filtered through Celite, washed with water (3 × 40 mL), and dried ($MgSO_4$). Crystallization of the crude product from $CH_2Cl_2-Et_2O$ gave the 1:1 mixture of 8a,b as yellow crystals: $[\alpha]_D$ −43° (*c* 1.0, $CH_2Cl_2$); 0.269 g (68% yield). Other physical properties are the same as 4a,b.

Optically pure diphosphine (*R*)-(+)-prophos was obtained from the 1:1 mixture of **8a**,**b** by the same procedures used for the liberation of its enantiomeric counterpart (*S*)-(−)-prophos from **4a**,**b**.

**Crystal Structure Determination of 4a,b.** A summary of the crystallographic analysis for **4a**,**b** is given in Table 2. The structures were analyzed at the National University of Singapore using a Siemens SMART CCD diffractometer with graphite-monochromated Mo Kα radiation. For complexes **4a**,**b**, semiempirical absorption corrections were applied. The crystal used for X-ray analysis is one consisting of both **4a**,**b**; i.e. it is a cocrystal of **4a**,**b**. The space group is *P*1. The asymmetric unit is the unit cell which contains one **4a** and one **4b**. The phenyl rings [C(18)−C(23) and C(24A−C(29A) of **4a**,**b**, respectively] were refined as rigid groups because of large anisotropic thermal parameters that gave poor distances. All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were introduced at fixed distance from carbon atoms and were assigned fixed thermal parameters. The absolute configurations of all chiral complexes were determined unambiguously using the Flack parameter.[31]

**Acknowledgment.** We are grateful to the National University of Singapore for support of this research and a research scholarship to W.-C.Y.

**Supporting Information Available:** For **4a**,**b**, tables of crystal data, data collection parameters, solution and refinement data, final postional parameters, bond distances and angles, thermal parameters of non-hydrogen atoms, and calculated hydrogen parameters and fully labeled ORTEP diagrams. This material is available free of charge via the Internet at http://pubs.acs.org.

IC040091R

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