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Novel chiral P,N-ferrocene ligands in palladium-catalyzed asymmetric allylic alkylations[1]

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Abstract

Novel chiral P,N-ferrocene ligands, 1-diphenylphosphino-1′-oxazolinylferrocenes, were prepared from ferrocene via 1,1′-bis(tributylstannyl)ferrocene and 1-diphenylphosphino-1′-methoxycarbonylferrocene as intermediates, and with this new kind of ligand up to 91% *ee* with 99% chemical yield was afforded for the palladium-catalyzed allylic alkylation of 1,3-diphenyl-2-propenyl acetate with dimethylmalonate anion. The complexation behavior of this kind of ligand with dichlorobis(acetonitrile)palladium and bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium was investigated.

1. Introduction

Recent publications from this laboratory have documented the synthesis and application of novel oxazoline ligands with multi stereogenic centres such as **1**,[2] **2**[3] and **3**;[4] besides the chirality of oxazoline groups, **1** also possesses the central chirality of the 1,3-dioxolane backbone derived from tartaric acid, **2** possesses the induced axial chirality of biphenyl on coordinating with a Cu(I) complex, and **3** possesses the planar chirality of ferrocene. Meanwhile, compound **4** with the planar chirality of ferrocene has been developed independently by several groups.[5] Compounds **3** and **4** have been proved to be effective P,N-ligands in several metal-catalyzed asymmetric reactions.[4,5] In contrast to **3** and **4**, we here wish to report the synthesis and application of a new kind of chiral P,N-ferrocene ligand **5**, 1-diphenylphosphino-1′-oxazolinylferrocenes, in which the phosphine and the oxazoline groups are attached to the two different Cp rings of ferrocene. Although this kind of ligand has no planar chirality on the ferrocene backbone, on coordinating with a metal, it may give two diastereomeric complexes because of the opposite twists of the Cp rings, and therefore, the complexes should possess a new chirality induced by the Cp ring twist. This design is just like that of ligand **2** which does not possess a stable axial chirality because of the rotation

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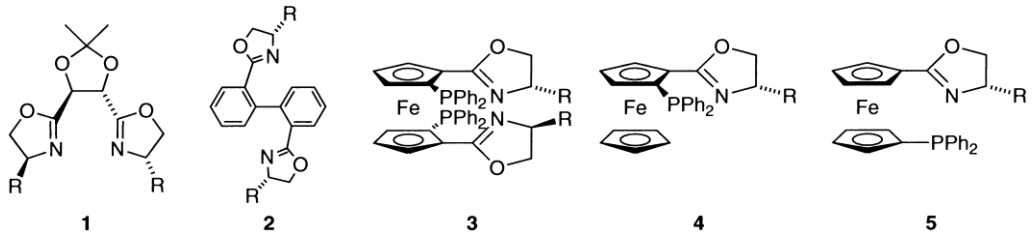
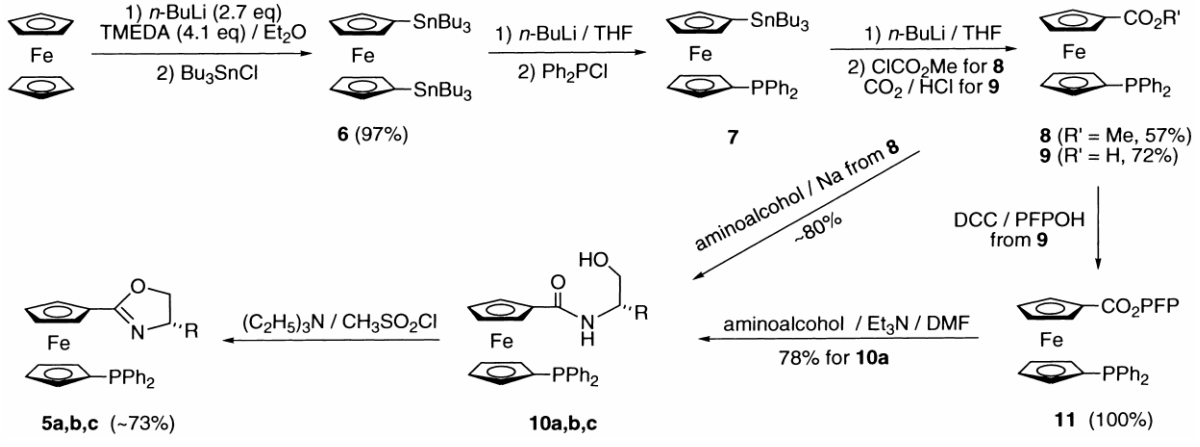


Fig. 1.

around the internal bond of the biphenyl, but a stable axial chirality can be induced on coordinating with a metal (see Fig. 1).[3a]

2. Results and discussion

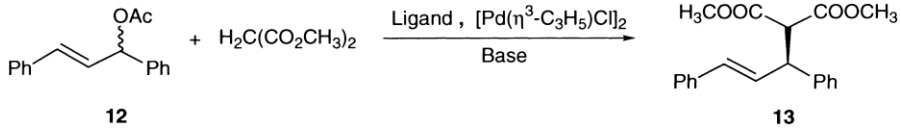
As shown in Scheme 1, ligands **5** were prepared with ease from ferrocene in several steps. Thus, ferrocene was dilithiated with a modified method[6] as shown in Scheme 1 and then trapped with tributyltin chloride to give 1,1′-bis(tributylstannyl)ferrocene **6** in 97% yield. Treatment of **6** with 1 molar equiv. of *n*-butyllithium in THF at −78°C for 1 h followed by reaction with chlorodiphenylphosphine afforded 1-diphenylphosphino-1′-tributylstannylferrocene **7**. Without isolation, this compound was again lithiated with 1 molar equiv. of *n*-butyllithium in THF at −78°C for 1 h followed by trapping with methyl chloroformate to afford 1-diphenylphosphino-1′-methoxycarbonylferrocene **8** in 57% yield from **6**. Treatment of the above lithiated species from **7** with dry ice followed by acidification with hydrochloric acid afforded 1-diphenylphosphino-1′-hydroxycarbonylferrocene **9** in 72% yield from **6**.[7] Compound **8** was reacted in neat chiral aminoalcohol at 100°C for 3 h in the presence of a small amount of sodium to give the corresponding amide **10** in good yields. Amide **10** can also be prepared with an alternative method from **9** in 78% yield via pentafluorophenyl (PFP) ester **11** as an intermediate.[8] Conversion of **10** to oxazoline **5** was accomplished via the corresponding mesylate as an intermediate which was cyclized in situ to the end product in good yields.[4a]



Scheme 1. (**a**, R=*i*-Pr; **b**,R=*t*-Bu; **c**, R=Ph)

Chiral P,N-ligands have been proved to be effective in several metal-catalyzed asymmetric reactions,[5,9,10] especially in the palladium-catalyzed allylic substitution.[10] In a previous study, we have found that chiral P,N-ferrocene ligands **3** and **4** are very effective in the palladium-catalyzed allylic

alkylation of 1,3-diphenyl-2-propenyl acetate.[4b] Here, we also chose this model reaction to test the effectiveness of compounds **5** as a new kind of P,N-ferrocene ligand (Scheme 2, Table 1).



Scheme 2.

It was known from Table 1 that this kind of ligand shows excellent catalytic activities and enantioselectivities. All of the reactions finished within 30 min to afford product **13** with above 96% isolated chemical yields regardless of the kind of base and solvent used. However, the base has a considerable influence on the enantioselectivities. When bis(trimethylsilyl)acetamide (BSA) was used, up to 91% *ee* was obtained with **5a** as a ligand (entry 1). However, only 43% *ee* was obtained when sodium hydride (NaH) was used with the same ligand (entry 2). This observation is very different from that with ligands **3** and **4**.[4b] The solvent also has some effects on enantioselectivities and dichloromethane attained higher *ee* than THF (entries 1, 3). In addition, the ligand structures have unusual influences on the enantioselectivities. For oxazoline ligands, higher enantiomeric excess was generally attained when the substituent on oxazoline ring was a *tert*-butyl group instead of an isopropyl group.[3,4b] However, **5a** with an isopropyl group on the oxazoline ring afforded higher *ee* than **5b** with a *tert*-butyl group on the oxazoline ring (entries 1, 4).

The complexation behavior of **5a** with dichlorobis(acetonitrile)palladium and bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium was examined by ^{1}H and ^{31}P NMR. When **5a** was complexed with 1 molar equiv. of dichlorobis(acetonitrile)palladium(II) in acetonitrile-d_3, two sets of signals in a ratio of 68:32 were shown in both ^{1}H and ^{31}P NMR spectra which might be assigned as diastereomers **14** and **15** (Fig. 2), respectively, according to an examination by MM2 calculations. Because of the opposite twists of the Cp rings of the ligand and the coordinating directions of allyl moiety, ligand **5a** would give four possible allylic palladium complexes upon complexation with bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium. It has been known that addition of chloride ion in a catalytic amount can accelerate the process of the apparent allyl rotation,[10d] and for this reason, the (η^3-allyl)palladium chloride dimer was often used as a catalyst in allylic substitution.[10d] Therefore, we next examined the complexation behavior of **5a** directly with 1 molar equiv. of bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium in dichloromethane-d_2. In this case, the allylic palladium complexes formed should be the same as the intermediates of the catalytic reaction. As a result, two sets of signals in a ^{1}H NMR spectrum and two

Table 1
Palladium-catalyzed allylic alkylation of 1,3-diphenyl-2-propenyl acetate[a]

Entry	Ligand	Base	Solvent	Yield (%)[c]	ee (%)[d]	Enantiomer[e]
1	**5a**	BSA[b]	CH_2Cl_2	99	91	(S)-(-)
2	**5a**	NaH	CH_2Cl_2	96	43	(S)-(-)
3	**5a**	BSA[b]	THF	99	87	(S)-(-)
4	**5b**	BSA[b]	CH_2Cl_2	97	57	(S)-(-)
5	**5c**	BSA[b]	CH_2Cl_2	96	71	(S)-(-)

a) Conducted at 25 °C with **12** (1 mmol), dimethylmalonate (3 mmol), base (3 mmol), ligand (21 μmol), and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (10 μmol) in 2 mL of solvent and all of the reactions finished within 30 min. b) Where KOAc (20 μmol) was added. c) Isolated yields. d) Determined by HPLC (Chiralcel OD®). e) Determined by comparing the sign of its optical rotation with literature data.[11]

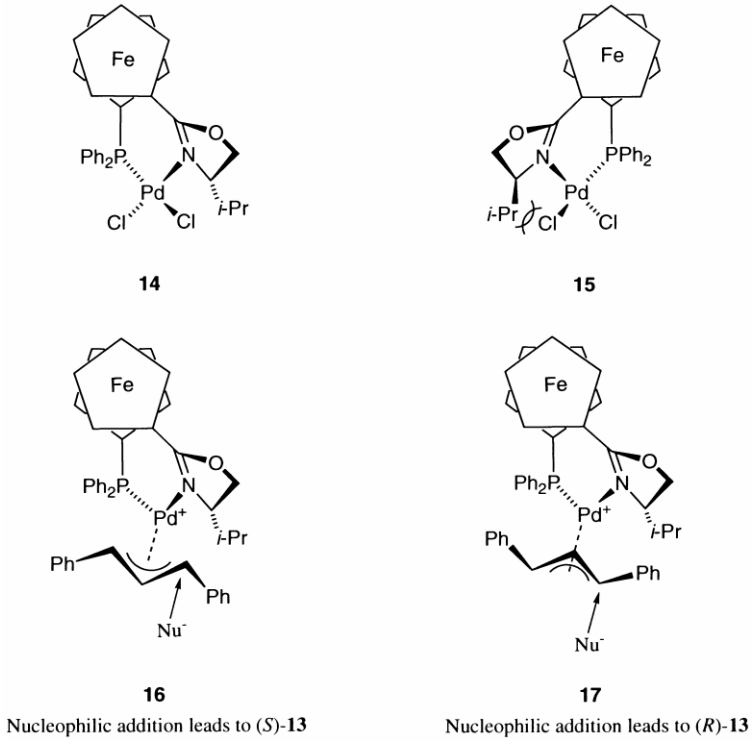


Fig. 2.

singlets (δ −120.9, −127.4) in a ratio of 96:4 in a ^{31}P NMR spectrum were observed at room temperature. At 0°C, the larger singlet (δ −120.9) in the ^{31}P NMR spectrum split into two singlets (δ −120.9 and −121.0) in a ratio of 1:1 and the ratio of the split singlets (δ −120.9 and −121.0) and the other singlet (δ −127.4) became 90:10. These results showed that two pairs of allylic palladium complexes could be formed and the major one might be assigned as those with a lower steric repulsion having **14**-like Cp ring twist, that is, **16** and **17** (Fig. 2), and that the apparent allyl rotation between **16** and **17** was sufficiently fast to give only one set of signals in both ^{1}H and ^{31}P NMR spectra at room temperature. From the result that the (*S*)-enantiomer was the predominant product at room temperature and the fact that the *trans* influence directs nucleophilic addition to the allyl terminus *trans* to the phosphorus atom,[12] it can be suggested that the reaction in this case proceeds predominantly via **16** as the main intermediate.

The enantioselectivities obtained with ligands **5** for the palladium-catalyzed allylic alkylation of 1,3-diphenyl-2-propenyl acetate (Table 1) were not better than those obtained with ligands **3** or **4**, which afforded up to 99% *ee* and 96% *ee*, respectively, for the same allylic alkylation.[4b] This may be because of the opposite twists of the Cp rings of ligands **5** upon complexation with palladium. Thus, ligands **5** probably produce more kinds of intermediates than **3** or **4**.

In summary, we have prepared a new kind of P,N-ferrocene ligand in which the P- and the N-groups were attached to the two different Cp rings of ferrocene. With this new kind of ligand, the palladium-catalyzed allylic alkylation of 1,3-diphenyl-2-propenyl acetate was carried out and up to 91% *ee* with 99% chemical yield was attained for product **13**. It was found that the substituent on oxazoline ring has unusual effects on the enantioselectivities and the ligand with an isopropyl group attained the highest enantioselectivity. It was also found that the base has great influences on enantioselectivities and BSA attained higher *ee* than NaH. The complexation behavior of ligand **5a**

with dichlorobis(acetonitrile)palladium and bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium was also investigated.

3. Experimental

Melting points were measured on a Yanagimoto micromelting point apparatus and have not been corrected. Optical rotations were measured on a DIP-181 digital polarimeter. ^{1}H NMR spectra were recorded on a JEOL GSX-400 spectrometer and the chemical shifts were referenced to $CHCl_3$ (δ 7.27) in $CDCl_3$, $CHDCl_2$ (δ 5.32) in CD_2Cl_2, and CHD_2CN (δ 1.93) in CD_3CN. ^{31}P NMR spectra were recorded on a JEOL GSX-400 spectrometer operating at 162 MHz and the chemical shifts were referenced to external $P(OMe)_3$ (δ 0.00). IR spectra were obtained on a HITACHI 260-10 infrared spectrophotometer. The fast atom bombardment mass spectra (FABMS) and high-resolution mass spectra (HRMS) were obtained on a JEOL JMS-DX303HF spectrometer.

THF was freshly distilled from sodium, dichloromethane from P_2O_5, DMF, TMEDA and triethylamine from CaH_2 before use. Aminoalcohols were prepared by reduction of the corresponding commercially available amino acids with $LiAlH_4$ as a reducing agent.[13] Bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium was prepared by a reported method.[14] All of the other chemicals used in synthetic procedures were of reagent grade. Merck 70–230 mesh silica gel was used for column chromatography. TLC plastic sheet (Silica gel 60 F_{254}) was used for the determination of R_f. All of the reactions were carried out under an argon atmosphere.

3.1. 1,1′-Bis(tributylstannyl)ferrocene **6**

A solution of ferrocene (10.0 g, 53.8 mmol) in ether (180 ml) was added dropwise to a mixture of *n*-butyllithium (1.6M in pentane, 90 ml, 144 mmol) and TMEDA (25.8 g, 222 mmol) at 0°C and the solution was then stirred at room temperature overnight to give a slurry of dilithiated ferrocene species. This ether slurry was treated with tributyltin chloride (39.8 g, 122 mmol) at −78°C and then warmed to room temperature over an 8-h period. The reaction mixture was washed with water (150 ml) and then with brine (150 ml) and dried over Na_2SO_4. The solvent was removed under reduced pressure to give a liquid residue, which was distilled under reduced pressure (0.08 torr, 200–210°C) to afford pure **6** as an oil (39.8 g, 52.1 mmol, 97%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.26 (4H, t, J=1.6 Hz, FcH), 3.99 (4H, t, J=1.6 Hz, FcH), 1.59 (12H, m, CH_2), 1.38 (12H, m, CH_2), 1.04 (12H, m, CH_2), 0.94 (18H, t, J=7.3 Hz, CH_3).

3.2. 1-Diphenylphosphino-1′-methoxycarbonylferrocene **8**

To a solution of **6** (3.0 g, 3.93 mmol) in THF (30 ml) was added dropwise *n*-butyllithium (1.6M in pentane, 2.48 ml, 3.96 mmol) at −78°C. The reaction mixture was stirred for an additional 1 h and then trapped with chlorodiphenylphosphine (0.874 g, 3.96 mmol) at this temperature. After stirring at room temperature for 2 h, the mixture was treated again with *n*-butyllithium (1.6M in pentane, 2.48 ml, 3.96 mmol) at −78°C for 1 h followed by trapping with methyl chloroformate (0.412 g, 4.36 mmol) at that temperature. After the cooling bath was removed, the mixture was stirred at room temperature overnight. After the solvent was removed, the residue was dissolved in hexane (150 ml). The solution was washed with water (150 ml) and then with brine (150 ml) and dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was purified by column chromatography with ethyl acetate:hexane

(1:10) as an eluent to afford **8** (0.96 g, 2.24 mmol, 57% from **6**). R_f=0.19 (ethyl acetate:hexane 1:10). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38–7.31 (10H, m, ArH), 4.72 (2H, t, *J*=2.0 Hz, FcH), 4.40 (2H, t, *J*=1.8 Hz, FcH), 4.28 (2H, t, *J*=2.0 Hz, FcH), 4.14 (2H, t, *J*=1.8 Hz, FcH), 3.78 (3H, s, CH_3). IR (neat) 3051, 2949, 1720, 1466, 1281, 1140, 775, 698 cm^{-1}. FABMS (*m/z*) 429 (M+1).

3.3. 1-Diphenylphosphino-1′-hydroxycarbonylferrocene **9**

To a solution of **6** (9.0 g, 11.8 mmol) in THF (100 ml) was dropped *n*-butyllithium (1.6M in pentane, 7.44 ml, 11.9 mmol) at −78°C. The reaction mixture was stirred for an additional 1 h and then trapped with chlorodiphenylphosphine (2.54 g, 11.5 mmol) at this temperature. After stirring at room temperature for 2 h, the mixture was treated again with *n*-butyllithium (1.6M in pentane, 7.44 ml, 11.9 mmol) at −78°C followed by stirring at that temperature for an additional 2 h. The reaction mixture was added to dry ice in ether (100 ml). After the dry ice disappeared, 6N HCl was added until pH=2. The organic layer was separated and the water layer was extracted with dichloromethane (100 ml×2). The organic layer was combined and dried over Na_2SO_4. After the solvent was removed under reduced pressure, the residue was purified by column chromatography with ethyl acetate as an eluent to afford **9** (3.50 g, 8.45 mmol, 72% from **6**). R_f=0.34 (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (10H, m, ArH), 4.76 (2H, t, *J*=2.0 Hz, FcH), 4.46 (2H, t, *J*=1.7 Hz, FcH), 4.34 (2H, t, *J*=1.8 Hz, FcH), 4.18 (2H, q, *J*=1.8 Hz, FcH).

3.4. 1-Diphenylphosphino-1′-[(S)-N-(1-isopropyl-2-hydroxyethyl)amido]ferrocene **10a** from **8**

A mixture of **8** (0.50 g, 1.17 mmol), (*S*)-valinol (0.36 g, 3.51 mmol), and a small amount of sodium was heated at 100°C for 3 h. The mixture was diluted with dichloromethane (100 ml) and neutralized with acetic acid. The neutralized solution was washed with water and then with brine and dried over Na_2SO_4. After the solvent was removed under reduced pressure, the residue was purified by column chromatography with ethyl acetate as an eluent to afford **10a** (0.42 g, 0.84 mmol, 72%). R_f=0.52 (ethyl acetate). mp 134.0–135.5°C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44–7.33 (10H, m, ArH), 6.02 (1H, d, *J*=9.2 Hz, NH), 4.64 (1H, m, FcH), 4.53 (1H, m, FcH), 4.51 (1H, m, FcH), 4.42 (1H, m, FcH), 4.25 (1H, m, FcH), 4.21 (1H, m, FcH), 4.16 (1H, m, FcH), 4.07 (1H, m, FcH), 3.83 (2H, m, NCH and OCH), 3.72 (1H, dd, *J*=6.2, 11.5 Hz, OCH), 1.98 (1H, m, $CHMe_2$), 1.04 (3H, d, *J*=7.0 Hz, CH_3), 1.02 (3H, d, *J*=7.0 Hz, CH_3). ^{31}P NMR ($CDCl_3$) δ −158.8. IR (KBr) 2958, 2869, 1621, 1538, 1432, 1386, 1311, 1160, 1060, 1025, 817, 742, 696 cm^{-1}. FABMS (*m/z*) 500 (M+1).

3.5. 1-Diphenylphosphino-1′-[(S)-N-(1-tert-butyl-2-hydroxyethyl)amido]ferrocene **10b** from **8**

Following a procedure identical to that described for the preparation of **10a**, the reaction of **8** (1.05 g, 2.45 mmol), (*S*)-*tert*-leucinol (0.86 g, 7.35 mmol), and a small amount of sodium afforded **10b** (1.00 g, 1.95 mmol, 80%) after purification by column chromatography with ethyl acetate as an eluent. R_f=0.47 (ethyl acetate). mp 169.0–170.1°C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45–7.31 (10H, m, ArH), 6.08 (1H, d, *J*=8.4 Hz, NH), 4.64 (1H, m, FcH), 4.52 (2H, m, FcH), 4.42 (1H, m, FcH), 4.26 (1H, m, FcH), 4.22 (2H, m, FcH), 4.06 (1H, m, FcH), 3.94 (2H, m, NCH and OCH), 3.65 (1H, m, OCH), 1.04 (9H, s, CH_3). ^{31}P NMR ($CDCl_3$) δ −158.8. IR (KBr) 2965, 1616, 1558, 1432, 1305, 1056, 1027, 831, 742, 696 cm^{-1}. FABMS (*m/z*) 514 (M+1).

3.6. 1-Diphenylphosphino-1′-[(S)-N-(1-phenyl-2-hydroxyethyl)amido]ferrocene **10c** from **8**

Following a procedure identical to that described for the preparation of **10a**, the reaction of **8** (0.50 g, 1.17 mmol), (*S*)-2-phenylglycinol (0.48 g, 3.51 mmol), and a small amount of sodium afforded **10c** (0.39 g, 0.74 mmol, 63%) after purification by column chromatography with ethyl acetate as an eluent. R_f=0.49 (ethyl acetate). mp 141.0–142.5°C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43–7.30 (15H, m, ArH), 6.52 (1H, d, *J*=7.8 Hz, NH), 5.23 (1H, dd, *J*=5.9, 11.7 Hz, OCH), 4.64 (1H, m, FcH), 4.58 (1H, m, FcH), 4.43 (1H, m, FcH), 4.39 (1H, m, FcH), 4.24 (1H, m, FcH), 4.22 (1H, m, FcH), 4.13 (1H, m, FcH), 4.03 (1H, m, FcH), 3.99 (2H, m, OCH and NCH). ^{31}P NMR ($CDCl_3$) δ −158.8. IR (KBr) 1627, 1531, 1378, 1294, 1160, 1070, 1027, 835, 740, 696 cm^{-1}. FABMS (*m/z*) 534 (M+1).

3.7. 1-Diphenylphosphino-1′-pentafluorophenoxycarbonylferrocene **11**

To a solution of **9** (0.415 g, 1.00 mmol) in THF (3 ml) at room temperature was added a solution of pentafluorophenol (0.276 g, 1.50 mmol) in THF (1 ml) followed by a solution of 1,3-dicyclohexylcarbodiimide (0.227 g, 1.10 mmol) in THF (1 ml). The reaction mixture was allowed to stir for 0.5 h, and the solution was then concentrated. The residue was dissolved in dichloromethane (50 ml), and the dicyclohexylurea precipitated was removed by filtration. The filtrate was washed with 5% NaOH (15 ml), water (15 ml), and brine (15 ml), dried over Na_2SO_4, and concentrated under reduced pressure to provide **11** (0.581 g, 1.00 mmol, 100%) which was used without further purification. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37–7.33 (10H, m, ArH), 4.88 (2H, brs, FcH), 4.56 (2H, brs, FcH), 4.46 (2H, brs, FcH), 4.27 (2H, brs, FcH). ^{31}P NMR ($CDCl_3$) δ −159.4.

3.8. **10a** from **11**

To a solution of **11** (0.581 g, 1.00 mmol) and (*S*)-valinol (0.382 g, 3.70 mmol) in DMF (10 ml) was added triethylamine (0.56 ml, 0.41 g, 4.05 mmol) via syringe at room temperature. The reaction mixture was heated at 80°C for 1 h and then cooled to room temperature. After diluting with dichloromethane (30 ml), the reaction solution was washed with water (30 ml) and brine (30 ml), dried over Na_2SO_4, and concentrated under reduced pressure to provide a residue which was purified by column chromatography to afford **10a** (0.388 g, 0.78 mmol, 78%).

3.9. 1-Diphenylphosphino-1′-[(S)-4-isopropyloxazolin-2-yl]ferrocene **5a**

To a solution of **10a** (0.62 g, 1.24 mmol) and triethylamine (0.70 ml, 0.51 g, 5.04 mmol) in dichloromethane (10 ml) was added methanesulfonyl chloride (0.14 g, 1.24 mmol) at 0°C. After stirring at room temperature for 2 h, the reaction solution was washed with chilled water (10 ml) and brine (10 ml), dried over Na_2SO_4, and concentrated under reduced pressure to provide a residue which was purified by column chromatography with ethyl acetate:hexane (1:1) as an eluent to afford **5a** (0.44 g, 0.91 mmol, 73%). R_f=0.40 (ethyl acetate:hexane 1:1). $[\alpha]_D^{24}$ −85.0 (*c* 1.87; $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39–7.31 (10H, m, ArH), 4.68 (2H, m, FcH), 4.39 (2H, t, *J*=1.8 Hz, FcH), 4.27 (1H, dd, *J*=8.0, 9.6 Hz, OCH), 4.20 (2H, m, FcH), 4.13 (2H, m, FcH), 4.05–3.94 (2H, m, OCH and NCH), 1.84 (1H, m, $CHMe_2$), 0.99 (3H, d, *J*=7.0 Hz, CH_3), 0.91 (3H, d, *J*=7.0 Hz, CH_3). ^{31}P NMR ($CDCl_3$) δ −158.9. IR (KBr) 2958, 2869, 1654, 1479, 1432, 1378, 1301, 1160, 1110, 1025, 966, 829, 742, 696 cm^{-1}. FABMS (*m/z*) 482 (M+1). HRMS (EI) calcd for $C_{28}H_{28}NOPFe$ 481.1371, found 481.1261.

3.10. 1-Diphenylphosphino-1′-[(S)-4-tert-butyloxazolin-2-yl]ferrocene **5b**

Following a procedure identical to that described for the preparation of **5a**, the reaction of **10b** (0.257 g, 0.50 mmol), triethylamine (0.28 ml, 0.20 g, 1.98 mmol), and methanesulfonyl chloride (0.057 g, 0.50 mmol) in dichloromethane (10 ml) afforded **5b** (0.12 g, 0.24 mmol, 48%) after purification by column chromatography with ethyl acetate:hexane (1:1) as an eluent. R_f=0.49 (ethyl acetate:hexane 1:1). $[\alpha]_D^{24}$ −131.8 (*c* 0.30; $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40–7.30 (10H, m, ArH), 4.69 (1H, m, FcH), 4.66 (1H, m, FcH), 4.40 (2H, m, FcH), 4.24–4.09 (6H, m, FcH and OCH), 3.88 (1H, dd, *J*=7.7, 10.1 Hz, NCH), 0.94 (9H, s, CH_3). ^{31}P NMR ($CDCl_3$) δ −158.8. IR (KBr) 2960, 1656, 1477, 1432, 1261, 1160, 1114, 1027, 966, 740, 696 cm^{-1}. FABMS (*m/z*) 496 (M+1). HRMS (EI) calcd for $C_{29}H_{30}NOPFe$ 495.1416, found 495.1409.

3.11. 1-Diphenylphosphino-1′-[(S)-4-phenyloxazolin-2-yl]ferrocene **5c**

Following a procedure identical to that described for the preparation of **5a**, the reaction of **10c** (0.36 g, 0.67 mmol), triethylamine (0.38 ml, 0.27 g, 2.67 mmol), and methanesulfonyl chloride (0.077 g, 0.67 mmol) in dichloromethane (10 ml) afforded **5c** (0.22 g, 0.43 mmol, 64%) after purification by column chromatography with ethyl acetate:hexane (1:1) as an eluent. R_f=0.44 (ethyl acetate:hexane 1:1). $[\alpha]_D^{24}$ −97.4 (*c* 0.80; $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42–7.28 (15H, m, ArH), 5.24 (1H, dd, *J*=8.1, 9.9 Hz, OCH), 4.81 (1H, m, FcH), 4.79 (1H, m, FcH), 4.69 (1H, dd, *J*=8.4, 9.9 Hz, OCH), 4.46 (2H, m, FcH), 4.28 (2H, t, *J*=1.8 Hz, FcH), 4.19 (3H, m, NCH and FcH). ^{31}P NMR ($CDCl_3$) δ −159.0. IR (KBr) 1650, 1479, 1432, 1378, 1159, 1114, 1025, 954, 831, 815, 777, 696 cm^{-1}. FABMS (*m/z*) 516 (M+1). HRMS (EI) calcd for $C_{31}H_{26}NOPFe$ 515.1103, found 515.1094.

3.12. General procedure for palladium-catalyzed allylic alkylation

A mixture of ligand **5a** (10.1 mg, 0.021 mmol) and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (3.7 mg, 0.010 mmol) in dry dichloromethane (1 ml) was stirred at room temperature for 1 h and the resulting yellow solution was added to a mixture of acetate **12** (0.252 g, 1.00 mmol) and potassium acetate (0.002 g, 0.02 mmol) in dry dichloromethane (1 ml) via cannula followed by the addition of dimethyl malonate (0.396 g, 3.00 mmol) and BSA (0.613 g, 3.00 mmol). When NaH was used as a base instead of BSA, the catalyst solution was added to a mixture of acetate **12** (0.252 g, 1.00 mmol) and dimethyl sodiummalonate prepared from dimethyl malonate (0.396 g, 3.00 mmol) and NaH (72% in nujol, 0.100 g, 3.00 mmol). The reactions were carried out at room temperature and monitored by TLC for the disappearance of acetate **12** (**12**: R_f=0.42, **13**: R_f=0.30, ethyl acetate:hexane 3:1). When all of the acetate **12** had been converted to the product (within 30 min), the solvent was evaporated and the resulting mixture was extracted with ether (50 ml). The extract was washed with saturated aq. NH_4Cl solution (50 ml) two times and then dried over Na_2SO_4. After removal of the ether the residue was purified by column chromatography with ethyl acetate:hexane (1:3) as an eluent to give pure product **13**. ^{1}H NMR (600 MHz, $CDCl_3$): δ 7.32–7.19 (10H, m, ArH), 6.44 (1H, d, *J*=15.8 Hz, PhCH=C), 6.30 (1H, dd, *J*=8.8, 15.8 Hz, PhC=CH), 4.27 (1H, dd, *J*=8.8, 10.7 Hz, $(CO_2Me)_2CCH$), 3.93 (1H, d, *J*=10.7 Hz, $(CO_2Me)_2CH$), 3.70 (3H, s, CH_3), 3.52 (3H, s, CH_3). The enantiomeric excess was determined by HPLC analysis [Chiralcel OD®, 25 cm × 0.46 cm; hexane:isopropanol (99.5:0.5); flow rate=0.9 ml/min; t_R=19.8 min (*R*-**13**), t_R=21.1 min (*S*-**13**)]. The absolute stereochemistry of the product was determined by comparing the sign of its specific rotation with literature data.[11]

3.13. Complexation behavior of **5a** with dichlorobis(acetonitrile)palladium(II)

A mixture of **5a** (4.8 mg, 0.01 mmol) and dichlorobis(acetonitrile)palladium(II) (2.6 mg, 0.01 mmol) was dissolved in acetonitrile-d_3 (0.5 ml) to give a solution. Both the ^{1}H and ^{31}P NMR of this solution showed two sets of signals in a ratio of 68:32, which might be assigned as diastereomers, **14** and **15**, respectively. **14**: ^{1}H NMR (400 MHz, CD_3CN): δ 7.91–7.37 (10H, m, ArH), 6.48 (1H, brs, FcH), 5.84 (1H, brs, FcH), 5.12 (1H, brs, FcH), 4.98–4.75 (6H, m, FcH and NCH), 3.99 (1H, dd, *J*=6.8, 9.4 Hz, OCH), 3.24 (1H, t, *J*=9.4 Hz, OCH), 2.89 (1H, m, Me_2CH), 0.86 (3H, d, *J*=7.0 Hz, CH_3), 0.67 (3H, d, *J*=6.6 Hz, CH_3). ^{31}P NMR (CD_3CN) δ −124.9. **15**: ^{1}H NMR (400 MHz, CD_3CN): δ 7.91–7.37 (10H, m, ArH), 6.39 (1H, brs, FcH), 5.06 (1H, brs, FcH), 4.98–4.75 (5H, m, FcH), 4.55 (1H, t, *J*=9.2 Hz, OCH), 4.49 (1H, brs, FcH), 4.01 (1H, m, NCH), 3.69 (1H, dd, *J*=9.2, 12.2 Hz, OCH), 2.53 (1H, m, Me_2CH), 1.70 (3H, d, *J*=6.2 Hz, CH_3), 0.47 (3H, d, *J*=6.2 Hz, CH_3). ^{31}P NMR (CD_3CN) δ −127.3. FABMS for the mixture of **14** and **15** (*m/z*) 659 (M+1). For comparison of **14** and **15** with **5a**, the ^{1}H NMR data of **5a** in CD_3CN are as follows: ^{1}H NMR (400 MHz, CD_3CN): δ 7.37–7.33 (10H, m, ArH), 4.56 (2H, t, *J*=2.0 Hz, FcH), 4.41 (2H, t, *J*=1.8 Hz, FcH), 4.27 (1H, dd, *J*=8.3, 9.5 Hz, OCH), 4.18 (1H, brs, FcH), 4.08 (2H, brs, FcH), 3.98 (1H, t, *J*=8.3 Hz, OCH), 3.86 (1H, m, NCH), 1.71 (2H, m, Me_2CH), 0.95 (3H, d, *J*=7.0 Hz, CH_3), 0.88 (3H, d, *J*=6.6 Hz, CH_3).

3.14. Complexation behavior of **5a** with bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium

A mixture of **5a** (14.6 mg, 0.030 mmol) and bis(μ-chloro)(1,3-diphenyl-η^3-allyl)dipalladium (10.2 mg, 0.015 mmol) in dichloromethane-d_2 (0.5 ml) was stirred at room temperature for 10 min to give a solution. This solution gave two sets of signals in a ^{1}H NMR spectrum and two singlets in a ratio of 96:4 in a ^{31}P NMR spectrum at room temperature. ^{1}H NMR (400 MHz, CD_2Cl_2) δ 7.75–6.81 (20H, m, ArH), 6.39 (1H, t, *J*=11.9 Hz, 2-H of allyl), 5.61 (1H, d, *J*=11.7 Hz, 1-H or 3-H of allyl), 4.83–4.15 (8H, m, FcH), 4.47 (1H, d, 1-H or 3-H of allyl), 4.29 (1H, dd, OCH), 4.03–3.89 (2H, m, OCH and NCH), 1.74 (1H, m, Me_2CH), 0.98 (3H, d, *J*=6.6 Hz, CH_3), 0.89 (3H, d, *J*=6.4 Hz, CH_3) (major). ^{31}P NMR (CD_2Cl_2) δ −120.9 (major), −127.4 (minor). At 0°C, ^{31}P NMR (CD_2Cl_2) δ −120.9 and −121.0 (major), −127.4 (minor).

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