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Synthesis of chiral 1′-substituted oxazolinylferrocenes as chiral ligands for Pd-catalyzed allylic substitution reactions

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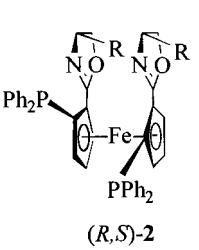
Abstract

Chiral 1-oxazolinyl-1′-(diphenylphosphino)ferrocenes **4** and 1-oxazolinyl-1′-(phenylthio)ferrocenes **5** were prepared from 1,1′-dibromoferrocene through 1-oxazolinyl-1′-bromoferrocenes **3**. The compounds **4** and **5** were employed as chiral ligands in Pd-catalyzed asymmetric allylic substitution reactions. High enantioselectivities (82–99% ee) and high yields (96–99%) were observed in the substitution reactions of 1,3-diphenylprop-2-enyl acetate and dimethyl malonate with the catalysts generated from $[(\pi\text{-allyl})PdCl]_2$ and **4**, while the use of **5** led to inferior results (20–75% ee and 25–28% yields). ^{1}H-, ^{13}C-, and ^{31}P-NMR data are analyzed for the complexes obtained from the reactions of $[(\eta^3\text{-allyl})PdCl]_2$ and $[(\eta^3\text{-1,3-diphenylallyl})PdCl]_2$ with **4a** and **4b**.

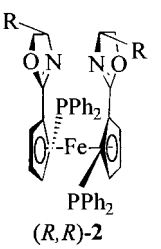
Keywords: 1′-Substituted oxazolinylferrocenes; *N*,*P*′-Chelate; Pd-catalysts; Allylic substitution

1. Introduction

Synthesis of chiral ferrocene derivatives has attracted much interest in various research fields [1]. Their distinct structural features have been found to be effective in many catalytic asymmetric reactions [2]. In recent years we have reported the syntheses of various chiral ferrocenes from oxazolinylferrocenes and 1,1′-bis-(oxazolinyl)ferrocenes through stereoselective ortho-lithiation and subsequent reactions with electrophiles [3–9].



(*R*,*S*)-**2**



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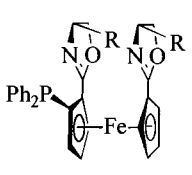
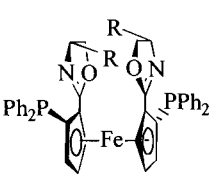


(*S*)-**1**

(*R*)-**1**



(*S*,*S*)-**2**

Amongst them, the phosphorylated derivatives have been employed as chiral ligands in Pd-catalyzed allylic substitution reactions [10–12]. The derivatives **1** and **2** have shown distinct reactivities. The differences can stem from various coordination modes of the ligands [10], which would be *N*,*P*-, *P*,*P*′-, *N*,*N*′- and *N*,*P*′-type chelations in forming Pd-catalysts. The Pd-catalysts derived from **1** are distinctively less effective than those from **2** as well as those from the *N*,*P*-type ligands such

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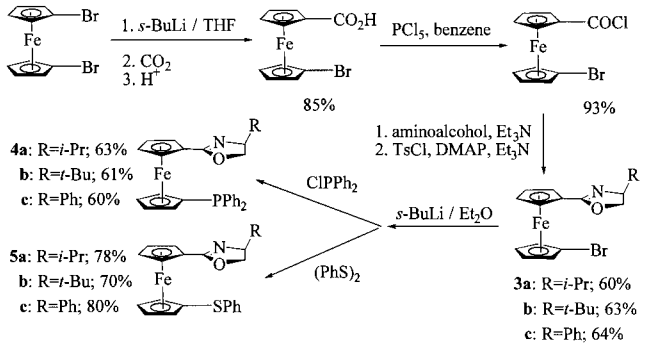


Scheme 1. Preparation of 1′-substituted 1-oxazolinylferrocenes.

as 1-oxazolinyl-2-(diphenylphosphino)ferrocenes and (phosphinoaryl)oxazolines. *N*,*N*′-type or *N*,*P*′-type chelation of **1** can be suspected as the reason for the inferior reactivity. However, the 1,1′-bis(oxazolinyl)-ferrocenes were found not to form active catalysts for the substitution reactions.

As an effort to obtain clues for effectiveness of the chelation provided by 1,1′-disubstituted ferrocene derivatives in the Pd-catalyzed asymmetric allylic substitution reactions, syntheses of chiral 1-oxazolinyl-1′-(diphenylphosphino)ferrocenes **4** and 1-oxazolinyl-1′-(phenylthio)ferrocenes **5** were carried out. Here we describe the synthetic procedures and the results obtained by using the ferrocene derivatives as chiral ligands in the Pd-catalyzed allylic substitution reactions.

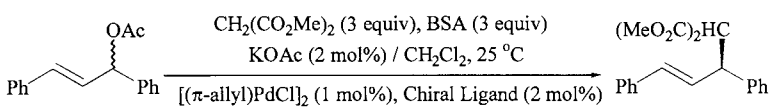
2. Results and discussion

As shown in Scheme 1, chiral *N*,*P*′-ligands **4** and *N*,*S*′-ligands **5** were prepared from 1,1′-dibromoferrocene through 1-bromo-1′-oxazolinylferrocenes **3**: 1,1′-dibromoferrocene was treated with one equivalent of *s*-BuLi, and the resulting lithiated species was carboxylated with dry ice to give 1-(1′-bromoferrocene)-carboxylic acid [13], which was converted to 1-bromo-1′-(chloro–carbonyl)ferrocene by the reaction with phosphorus pentachloride. The acid chloride was coupled with chiral aminoalcohols to give amides which were transformed to corresponding 1-bromo-1′-oxazolinylferrocenes **3** by the treatment with *p*-toluenesulfonyl chloride in the presence of *N*,*N*-dimethylaminopyridine and triethylamine. Lithiation of **3** followed by the reactions with chlorodiphenylphosphine and diphenyldisulfide provided **4** and **5**, respectively.

The Pd-catalyzed allylic substitution reactions were carried out with 1,3-diphenylprop-2-enyl acetate under standard conditions (Table 1) [10].

In all cases the major product had (*S*)-configuration. The catalysts generated with the *N*,*P*′-ligands **4** show much faster turnover rates and better enantioselectivity than those with *N*,*S*′-ligands **5**. The turnover rates of the reactions with **4** are also better than those with **1**, and are comparable to those with **2**. These results implicate that the inferior reactivity of ligands **1** is not due to an *N*,*P*′-type chelation and that the *N*,*P*′-chelation is as effective as the *P*,*P*′-chelation of (*S*,*S*)-**2** in the substitution reactions. The iso-propyl derivative **4a** appears to be the optimal ligand for 1,3-diphenylprop-

Table 1
Enantioselective Pd-catalyzed allylic substitution reactions with the ligands **4** and **5**



Ligand	Reaction time [a]	% ee (abs. Config.) [b]	Yield (%) [c]
(*S*)-**1** [d]	2 h	80 (*S*) [e]	88
(*R*)-**1** [d]	3 h	74 (*S*)	53
(*S*,*S*)-**2** [d]	10 min	94 (*S*)	99
(*R*,*S*)-**2** [d]	30 min	99 (*S*)	99
(*R*,*R*)-**2** [d]	10 min	34 (*S*)	99
4a	10 min	99 (*S*)	96
4b	30 min	82 (*S*)	99
4c	20 min	93 (*S*)	96
5a	6 days	20 (*S*)	25
5b	6 days	60 (*S*)	28
5c	6 days	75 (*S*)	28

[a] 0.3 M allylic acetate in CH_2Cl_2.
[b] Determined by HPLC (Chiralcel OD®).
[c] Purified yields by column chromatography on SiO_2.
[d] R = ^{t}Bu (see ref. [10]).
[e] The absolute configuration was assigned by comparing the sign of its optical rotation with literature data [14].

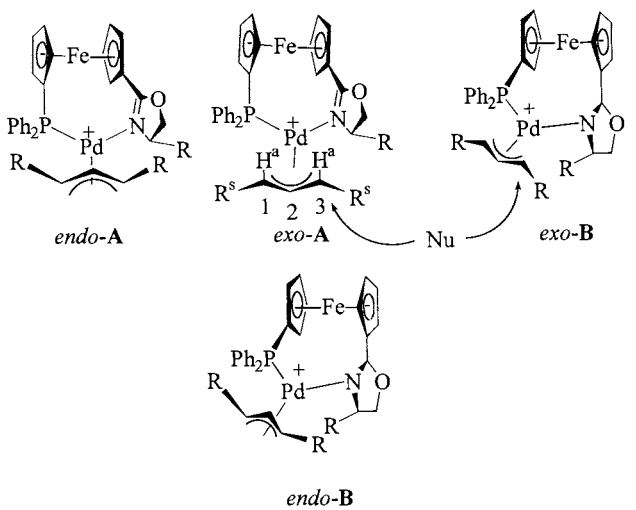
Table 2
Selected NMR data [a] of the Pd(II) complexes in CD_2Cl_2 at 25°C

Complex	^1H	^{13}C	^{31}P
[(η^3-allyl)Pd(**4a**)]Cl	5.66 (m; 2H), 4.72 (br s; 3H^s), 3.79 (br s; 3H^a), 3.08 (very br s; 1H^s, 1H^a)	118.5 (d, 2C), 80.5 (d, 3C), 60.3 (1C)	18.6
[(η^3-allyl)Pd(**4b**)]Cl	5.66 (m; 2H), 4.72 (br s; 3H^s), 3.86 (br dd; 3H^a), 3.32 (br s; 1H^s), 2.85 (br d; 1H^a)	118.2 (2C), 80.3 (d, 3C), 60.1 (1C)	18.6
[(η^3-1,3-diphenylallyl)Pd(**4a**)]Cl	6.41 (br dd; 2H), 5.63 (br d; 3H^a), 4.47 (br s; 1H^a)	110.2 (br; 2C), 99.2 (br, 3C), 73.5 (1C)	22.8
[(η^3-1,3-diphenylallyl)Pd(**4b**)]Cl	6.38 (br dd; 2H), 5.60 (br d; 3H^a), 4.57 (br d; 1H^a)	110.3 (br; 2C), 98.9 (br, 3C), 73.6 (1C)	22.9, 22.7

[a] The resonance peaks are assigned by the aid of 2-D NMR spectra (^1H, ^1H-COSY, DEPT, and ^1H, ^{13}C-COSY).

2-enyl acetate. In comparison with the results of the known (phosphinoaryl)-oxazolines, the turnover rates observed with **4** were two to six times faster and the enantioselectivities similar [15–17].

In order to characterize the catalytic species in the substitution reactions, the four complexes formed in the reactions of [(η^3-allyl)PdCl]$_2$ and [(η^3-1,3-diphenylallyl)PdCl]$_2$ with **4a** and **4b** were analyzed by ^1H-, ^{13}C-, and ^{31}P-NMR spectroscopy (Table 2). Palladium complexes are formed in virtually quantitative yields and are 1:1 adducts of π-allyl-Pd(II) moieties and **4**. In ^1H-NMR spectra obtained at room temperature (r.t.) only one set of peaks is observed in spite of at least four structures being possible, when the ligands **4** acts as *N*,*P*′-chelates, due to rotation of the cyclopentadienyl (Cp) rings and isomerization through the η^3–η^1 allyl rearrangement. In the case of [(η^3-allyl)Pd(**4a**)]Cl two protons of the allyl group appear as a very broad singlet which starts to split into two broad singlets of 1:1 ratio at about 0°C. The ^{13}C- and ^{31}P-NMR spectra also show only one set of peaks for the allyl groups except the ^{31}P-NMR spectrum of [(η^3-1,3-diphenylallyl)Pd(**4b**)]Cl in which two peaks of 1:1 ratio are observed.



The NMR data of [(η^3-allyl)Pd(**4a**)]Cl and [(η^3-allyl)Pd(**4b**)]Cl can be explained as the results from fast interconversion among the possible isomers at r.t. to give one set of resonance lines of average chemical shift values. In particular the coalescence for two protons in [(η^3-allyl)Pd(**4a**)]Cl, which is assigned to 1H^a and 1H^s [18], is consistent with the selective η^3–η^1 allyl isomerization [19] through opening of the Pd–C(3) bond *trans* to the phosphorus atom and rotation around the C(1)–C(2) bond. However, the *exo*-isomers seem to be predominant in the solutions of [(η^3-1,3-diphenylallyl)Pd(**4a**)]Cl and [(η^3-1,3-diphenylallyl)Pd(**4b**)]Cl with much slower η^3–η^1 allyl isomerization rates than those of the simple π-allyl complexes, because any new set of peaks for endo-isomers or coalescence was not observed at the region for the allyl group in the ^1H-NMR spectra by varying the temperature from 60 to −70°C. The two peaks of 1:1 ratio in the ^{31}P-NMR spectrum of [(η^3-1,3-diphenylallyl)Pd(**4b**)]Cl, which collapsed to a singlet at 60°C, can be assigned to two conformers, *exo*-**A** and *exo*-**B**. Based on the known fact that nucleophiles attack on the carbon *trans* to the Pd–P bond [19], the two conformers with *exo*-configuration can be suggested as the species responsible for the (*S*)-configuration of the predominant substitution product.

3. Conclusions

1-Oxazolinyl-1′-(diphenylphosphino)ferrocenes **4** and 1-oxazolinyl-1′-(phenylthio)ferrocenes **5** were synthesized and employed in Pd-catalyzed asymmetric allylic substitution reactions. While the *N*,*S*′-ligands **5** were found to be relatively poor in forming reactive Pd-catalysts, the catalysts derived from **4a** (R = ^{i}Pr) and **4c** (R = Ph) showed much more effective reactivities than those of known *N*,*P*-chelates such as 1-oxazolinyl-2-(diphenylphosphino)ferrocenes [10] and (phosphinoaryl)oxazolines [15–17]. In particular the catalyst derived from **4a** was as effective as that from the *P*,*P*′-chelate

(*S*,*S*)-**2** in turnover rate, and showed higher enantioselectivity.

^{1}H-, ^{13}C-, and ^{31}P-NMR data were analyzed for the complexes obtained from the reactions of $[(\eta^3$-allyl)PdCl$]_2$ and $[(\eta^3$-1,3-diphenylallyl)PdCl$]_2$ with **4a** and **4b**. The four complexes formed as 1:1 adducts of the π-allyl-Pd(II) species and the ligands. For the simple (π-allyl)Pd(II) complexes interconversion among isomers were fast enough to show only one set of resonance lines in ^{1}H-NMR spectra at r.t. through allyl isomerization as well as rotation of the Cp rings. However, the *exo*-isomers seem to be predominant with slow $\eta^3-\eta^1$ allyl isomerization in the solutions of $[(\eta^3$-1,3-diphenylallyl)Pd(**4a**)]Cl and $[(\eta^3$-1,3-diphenylallyl)Pd(**4b**)]Cl. The (*S*)-configuration of the predominant substitution product can be explained by the nucleophilic attack *trans* to the Pd–P bond of the *exo*-isomers.

4. Experimental

4.1. General

If not otherwise stated, all NMR spectra were recorded in $CDCl_3$. Chemical shifts are given in δ ppm downfield from TMS (δ 0, ^{1}H) or $CDCl_3$ (δ 77, ^{13}C) as an internal standard, and from aqueous 85% phosphoric acid solution (δ 0, ^{31}P) as an external standard. IR spectra were obtained with thin films on NaCl plates or with KBr pellets. Optical rotations were measured at 589 nm (sodium D line). Specific rotations ($[\alpha]_D$) are reported in degrees per decimeter at r.t., and the concentration (c) is given in g 100 ml^{-1} in the specified solvent. EI mass spectra were recorded on a Jeol JMS-AX505WA. Melting points are not corrected. Elemental analyses were performed by the Macromolecular Laboratory of Chemistry Department in Pohang University of Science and Technology.

All reactions and manipulations were carried out on a dual manifold providing vacuum and dry argon. 1-(1′-Bromoferrocene)carboxylic acid [13], $[(\eta^3$-allyl)PdCl$]_2$ [20], and $[(\eta^3$-1,3-diphenylallyl)PdCl$]_2$ [21] were prepared according to the literature procedures.

4.2. 1-Bromo-1′-[(S)-(4-iso-propyl-2,5-oxazolinyl)]-ferrocene (3a)

1-Bromo-1′-chlorocarbonyl–ferrocene (1.42 g, 4.34 mmol), (*S*)-(+)-valinol (0.58 g, 5.6 mmol), and triethylamine (1.8 ml, 13 mmol) were dissolved in dry CH_2Cl_2 (20 ml), and the resulting solution was stirred at 25°C for 30 min. Then, *p*-toluenesulfonyl chloride (1.40 g, 7.33 mmol) and triethylamine (1.8 ml, 13 mmol) were added to the solution, and the resulting mixture was heated to reflux for 10 h. The reaction mixture was diluted with CH_2Cl_2 (50 ml), washed with saturated aqueous NH_4Cl (30 ml), and dried over $MgSO_4$. The solvent was evaporated, and the resulting residue was chromatographed on silica gel (2:1 hexane:ethyl acetate) to give 0.98 g (2.6 mmol, 60%) of an orange gum, which could be crystallized from hexane at −20°C: m.p. (dec.) = 39–41°C. ^{1}H-NMR δ 4.79 (dd, $J_1 = 2.0$, $J_2 = 1.9$ Hz, 2H, Cp), 4.42 (m, 2H, Cp), 4.37 (m, 2H, Cp), 4.12 (dd, $J_1 = 1.9$, $J_2 = 1.8$ Hz, 2H, Cp), 4.32 (dd, $J_1 = 9.2$, $J_2 = 7.8$ Hz, 2H, –OC$\underline{H}_2$), 4.02 (m, 1H, =NC$\underline{H}$), 4.00 (m, 1H, –OC$\underline{H}_2$), 1.85 (m, 1H, –C$\underline{H}$(CH$_3$)$_2$), 1.01 (d, $J = 6.8$ Hz, 3H, –CH(C$\underline{H}_3$)$_2$), 0.92 (d, $J = 6.8$ Hz, 3H, –CH(C$\underline{H}_3$)$_2$); ^{13}C-NMR δ 165.2 (–$\underline{C}$=N), 79.2, 73.5, 73.5, 73.4, 73.1, 72.2, 72.1, 71.6, 70.2, 69.4 (Cp, –O$\underline{C}$H$_2$, =N$\underline{C}$H), 33.1 (–$\underline{C}$H(CH$_3$)$_2$), 19.7 (–CH($\underline{C}$H$_3$)CH$_3$), 18.6 (–CH(CH$_3$)$\underline{C}$H$_3$); IR (KBr) ν(C=N) 1657 cm^{-1}; $[\alpha]_D^{24} = -48.6°$ ($c = 0.50$, $CHCl_3$); MS m/z 375. Anal. Calc. for $C_{16}H_{18}NOFeBr$: C, 51.10; H, 4.82; N, 3.72. Found: C, 51.16; H, 4.86; N, 3.49%.

4.3. 1-Bromo-1′-[(S)-(4-tert-butyl-2,5-oxazolinyl)]-ferrocene (3b)

1-Bromo-1′-chlorocarbonyl–ferrocene (2.4 g, 7.3 mmol) and (*S*)-*tert*-leucinol (0.88 g, 7.5 mmol) were allowed to react according to the procedure for **3a** to give 1.79 g (4.60 mmol, 63%) of **3b** as a yellow solid, which could be recrystallized from hexane and a small amount of ether at −20°C: m.p. (dec.) = 112–113°C; ^{1}H-NMR δ 4.79 (dd, $J_1 = 2.4$, $J_2 = 1.2$ Hz, 1H, Cp), 4.76 (dd, $J_1 = 2.4$, $J_2 = 1.1$ Hz, 1H, Cp), 4.42 (s, br, 2H, Cp), 4.37 (m, 2H, Cp), 4.12 (t, $J = 1.90$ Hz, 2H, Cp), 4.27 (dd, $J = 10.1$, 8.6 Hz, 1H, –OC$\underline{H}_2$), 4.19 (dd, $J = 8.6$, 7.6 Hz, 1H, –OC$\underline{H}_2$), 3.91 (dd, $J_1 = 10.1$, $J_2 = 7.6$ Hz, 1H, =NC$\underline{H}$), 0.96 (s, 9H, –C(C$\underline{H}_3$)$_3$); ^{13}C-NMR δ 165.0 (–$\underline{C}$=N), 79.0, 77.0, 73.6, 73.5, 72.2, 72.0, 71.6, 69.4, 69.0 (Cp, –O$\underline{C}$H$_2$, =N$\underline{C}$H), 34.3 (–$\underline{C}$(CH$_3$)$_3$), 26.6 (–C($\underline{C}$H$_3$)$_3$); IR (KBr) 1663 cm^{-1}; $[\alpha]_D^{24} = -82.7°$ ($c = 0.49$, $CHCl_3$); EI MS: m/z 389. Anal. Calc. for $C_{17}H_{20}NOFeBr$: C, 52.34; H, 5.14; N, 3.59. Found: C, 52.13; H, 5.23; N, 3.31%.

4.4. 1-Bromo-1′-[(S)-4-phenyl-2,5-oxazolinyl]ferrocene (3c)

1-Bromo-1′-chlorocarbonyl–ferrocene (1.94 g, 5.92 mmol) and (*S*)-phenylglycinol (0.845 g, 6.16 mmol) were allowed to react according to the procedure for **3a** to give 1.57 g (3.85 mmol, 65%) of **3c** as an orange solid, which could be recrystallized from hexane and a small amount of ether at −20°C: m.p. (dec.) = 104–107°C; ^{1}H-NMR δ 7.38–7.25 (m, 5H, Ph), 5.26 (dd, $J_1 = 9.4$, $J_2 = 8.3$ Hz, 1H, –OCH(H)C$\underline{H}$), 4.87 (dd, $J_1 = 1.9$, $J_1 = 1.8$ Hz, 2H, Cp), 4.72 (dd, $J_1 = 9.4$, $J_2 = 8.9$ Hz, 1H, –OC$\underline{H}_2$), 4.47 (d, $J = 1.0$ Hz, 2H, Cp), 4.42 (d, $J = 1.3$ Hz, 2H, Cp), 4.21 (m, 1H, –OC$\underline{H}_2$), 4.16 (s,

br, 2H, Cp); ^{13}C-NMR δ 165.5 (–C=N), 142.9, 129.1, 128.0, 127.2, 127.1 (Ph), 79.1, 75.0, 73.4, 73.4, 72.1, 72.0, 71.9, 71.7, 70.5, 70.1, 69.2, 69.1 (Cp, –OCH$_2$, =NCH); IR (KBr) ν 1645 cm^{-1} (C=N); $[\alpha]_D^{24} = -60.8°$ (c = 0.52, $CHCl_3$); MS m/z 409. Anal. Calc. for $C_{19}H_{16}NOFeBr$: C, 55.65; H, 3.93; N, 3.42. Found: C, 55.24; H, 3.96; N, 3.30%.

4.5. 1-[(S)-4-Iso-propyl-2,5-oxazolinyl]-1′-(diphenylphosphino)ferrocene (**4a**)

Into a solution of **3a** (310 mg, 0.824 mmol) in ether (20 ml), *sec*-BuLi (1.30 M, 0.70 ml, 0.91 mmol) was added dropwise at −78°C, and the resulting solution was stirred at −78°C for 2 h. Then, chlorodiphenylphosphine (0.18 ml, 0.99 mmol) was added, and the resulting mixture was stirred and warmed to 25°C over 2 h. The reaction mixture was filtered through Celite, and the filtrate was concentrated and chromatographed on silica gel under an argon atmosphere to give 251 mg (0.521 mmol, 63%) of **4a** as an orange solid, which could be recrystallized from hexane at −78°C. m.p. (dec.) = 66–67.5°C; ^{1}H-NMR δ 7.38–7.25 (m, 10H, Ph), 4.67 (d, $J = 0.9$ Hz, 2H, Cp), 4.37 (m, 2H, Cp), 4.19 (m, 2H, Cp), 4.11 (m, 2H, Cp), 4.25 (dd, $J_1 = 8.9$, $J_2 = 7.8$ Hz, 1H, –OCH$_2$), 4.02 (dd, $J_1 = 7.8$, $J_2 = 7.6$ Hz, 1H, –OCH$_2$), 3.95 (m, 1H, =NCH), 1.82 (m, 1H, –CH(CH$_3$)$_2$), 0.98 (d, $J = 6.8$ Hz, 3H, –CH(CH$_3$)$_2$), 0.89 (d, $J = 6.8$ Hz, 3H, –CH(CH$_3$)$_2$); ^{13}C-NMR δ 165.6 (–C=N), 139.2, 139.1, 134.0, 133.8, 129.0, 128.9, 128.7, 128.6 (Ph), 78.0, 74.6, 74.5, 74.4, 74.3, 73.2, 73.1, 72.7, 72.0, 71.7, 70.3, 69.8 (Cp, –OCH$_2$, =NCH), 32.7 (–CH(CH$_3$)$_2$), 19.4 (–CH(CH$_3$)$_2$), 18.3 (–CH(CH$_3$)$_2$); ^{31}P-NMR δ −15.2; IR (neat), ν(C=N) 1655 cm^{-1}; $[\alpha]_D^{25} = -84.0°$ ($c = 0.46$, $CHCl_3$); MS m/z 481. Anal. Calc. for $C_{28}H_{28}NOPFe$: C, 69.87; H, 5.86; N, 2.91. Found: C, 69.83; H, 5.92; N, 2.60%.

4.6. 1-[(S)-4-tert-Butyl-2,5-oxazolinyl]-1′-(diphenylphosphino)ferrocene (**4b**)

Compound **3b** (339 mg, 0.869 mmol) was allowed to react according to the procedure for **4a** to give 258 mg (0.521 mmol, 60%) of **4b** as an orange solid, which could be recrystallized from hexane at −20°C: m.p. (dec.) = 115–116°C; ^{1}H-NMR δ 7.39–7.29 (m, 10H, Ph), 4.67 (dd, $J_1 = 2.4$, $J_2 = 1.2$ Hz, 1H, Cp), 4.66 (dd, $J_1 = 2.4$, $J_2 = 1.3$ Hz, 1H, Cp), 4.39 (s, br, 2H, Cp), 4.16 (m, 2H, Cp), 4.20 (dd, $J_1 = 10.1$, $J_2 = 18.7$ Hz, 1H, –OCH$_2$), 4.09 (dd, $J_1 = 8.7$, $J_2 = 7.6$ Hz, 1H, –OCH$_2$), 3.86 (dd, $J_1 = 10.1$, $J_2 = 7.6$ Hz, 1H, =NCH), 0.92 (s, 9H, –C(CH$_3$)$_3$). ^{13}C-NMR δ 165.5 (–C=N), 139.3, 139.2, 139.1, 139.0, 134.1, 134.0, 133.8, 133.7, 129.0, 128.9, 128.7, 128.6 (Ph), 76.5, 74.7, 74.5, 74.4, 74.2, 73.1, 72.0, 71.9, 70.4, 70.2, 68.8 (Cp, –OCH$_2$, =NCH), 34.0 (–C(CH$_3$)$_3$), 26.4 (–C(CH$_3$)$_3$); ^{31}P-NMR δ −15.1; IR (neat) ν(C=N) 1658 cm^{-1}; $[\alpha]_D^{25} = -134.3°$ ($c = 0.48$, $CHCl_3$); MS m/z 495. Anal. Calc. for $C_{29}H_{30}NOPFe$: C, 70.31; H, 6.10; N, 2.83. Found: C, 69.82; H, 6.15; N, 2.74%.

4.7. 1-[(S)-4-Phenyl-2,5-oxazolinyl]-1′-(diphenylphosphino)ferrocene (**4c**)

Compound **3c** (957 mg, 2.33 mmol) was allowed to react according to the procedure for **4a** to give 721 mg (1.40 mmol, 60%) of **4c** as an orange solid, which could be recrystallized from hexane at −20°C: m.p. (dec.) = 85–87°C; ^{1}H-NMR δ 7.39–7.30 (m, 15H, Ph), 5.20 (dd, $J_1 = 9.9$, $J_2 = 7.9$ Hz, 1H, =NCH), 4.78 (m, 1H, Cp), 4.75 (m, 1H, Cp), 4.43 (t, $J = 1.7$ Hz, 2H, Cp), 4.25 (t, $J = 1.9$ Hz, 2H, Cp), 4.16 (m, 2H, Cp), 4.66 (dd, $J_1 = 9.9$, $J_2 = 8.3$ Hz, 1H, –OCH$_2$), 4.16 (m, 1H, –OCH$_2$); ^{13}C-NMR δ 167.3 (–C=N), 143.0, 139.1, 139.0, 134.1, 133.8, 129.1, 129.0, 128.7, 128.6, 128.0, 127.2 (Ph), 78.3, 75.0, 74.7, 74.6, 74.5, 73.2, 72.3, 71.6, 70.6, 70.4, (Cp, –OCH$_2$, =NCH); ^{31}P-NMR δ −15.3; IR (neat) ν(C=N) 1650 cm^{-1}; $[\alpha]_D^{25} = -93.7°$ ($c = 0.4$, $CHCl_3$); MS m/z 515. Anal. Calc. for $C_{31}H_{26}NOPFe$: C, 72.25; H, 5.08; N, 2.72. Found: C, 72.17; H, 5.25; N, 2.32%.

4.8. 1-[(S)-4-Iso-propyl-2,5-oxazolinyl]-1′-(phenylthio)ferrocene (**5a**)

Into a solution of **3a** (407 mg, 1.08 mmol) in ether (20 ml), *sec*-BuLi (1.3 M, 0.92 ml, 1.2 mmol) was added dropwise at −78°C, and the resulting solution was stirred at −78°C for 2 h. Then, a solution of diphenyldisulfide (307 mg, 1.41 mmol) was added, and the resulting mixture was stirred and warmed to 25°C over 12 h. The reaction mixture was diluted with ether (50 ml), washed with saturated aqueous $NaHCO_3$, and dried over $MgSO_4$. The solvent was removed under reduced pressure, and the resulting residue was chromatographed on silica gel to give 342 mg (0.844 mmol, 78%) of **5a** as an orange solid, which could be recrystallized from hexane and a small amount of ether at −20°C: m.p. (dec.) = 75–76°C; ^{1}H-NMR δ 7.17 (m, 2H, Ph), 7.06 (m, 3H, Ph), 4.84 (m, 1H, Cp), 4.82 (m, 1H, Cp), 4.42 (m, 4H, Cp), 4.35 (m, 2H, Cp), 4.34 (dd, $J_1 = 9.4$, $J_2 = 8.0$ Hz, 1H, –OCH$_2$), 4.09 (dd, $J_1 = 8.0$, $J_2 = 7.7$ Hz, 1H, –OCH$_2$), 4.00 (m, 1H, =NCH), 1.88 (m, 1H, –CH(CH$_3$)$_2$), 1.01 (d, $J = 6.8$ Hz, 3H, –CH(CH$_3$)$_2$), 0.93 (d, $J = 6.8$ Hz, 3H, –CH(CH$_3$)$_2$); ^{13}C-NMR δ 165.2 (–C=N), 140.6, 129.0, 126.5, 125.4 (Ph), 76.6, 76.5, 72.9, 72.6, 72.3, 72.2, 72.1, 70.9, 70.7, 70.0 (Cp, –OCH$_2$, =NCH), 32.8 (–CH(CH$_3$)$_2$), 19.5 (–CH(CH$_3$)$_2$), 18.4 (–CH(CH$_3$)$_2$); IR (neat) ν(C=N) 1657 cm^{-1}; $[\alpha]_D^{24} = -73.4°$ ($c = 0.50$, $CHCl_3$); MS m/z 405. Anal. Calc. for $C_{22}H_{23}NOSFe$: C, 65.19; H, 5.72; N, 3.4. Found: C, 65.40; H, 5.78; N, 3.36%.

4.9. 1-[(S)-4-tert-Butyl-2,5-oxazolinyl]-1′-(phenylthio)-ferrocene (**5b**)

Compound **3b** (416 mg, 1.07 mmol) was allowed to react according to the procedures for **5a** to give 315 mg (0.751 mmol, 70%) of **5b** as a yellow solid, which could be recrystallized from hexane and a small amount of ether at −20°C: m.p. (dec.) = 90–91°C; ^{1}H-NMR δ 7.17 (m, 2H, Ph), 7.05 (m, 3H, Ph), 4.86 (dd, $J_1 = 1.2$, $J_2 = 0.8$ Hz, 1H, Cp), 4.80 (dd, $J_1 = 1.1$, $J_2 = 0.8$ Hz, 1H, Cp), 4.40 (m, 4H, Cp), 4.36 (dd, $J_1 = 1.8$, $J_2 = 1.7$ Hz, 2H, Cp), 4.28 (dd, $J_1 = 10.1$, $J_2 = 8.8$ Hz, 1H, –OC$\underline{H}_2$), 4.17 (dd, $J_1 = 8.8$, $J_2 = 7.6$ Hz, 1H, –OC$\underline{H}_2$), 3.92 (dd, $J = 10.1$, 7.6 Hz, 1H, =NC$\underline{H}$), 0.96 (s, 9H, –C(C$\underline{H}_3$)$_3$); ^{13}C-NMR δ 165.1 (–$\underline{C}$=N), 140.6, 129.0, 126.5, 125.4 (Ph), 76.6, 76.4, 72.7, 72.3, 72.2, 72.1, 70.9, 70.8, 68.9 (Cp, –O$\underline{C}$H$_2$, =N$\underline{C}$H), 34.1 (–$\underline{C}$(CH$_3$)$_3$), 26.4 (–C($\underline{C}$H$_3$)$_3$); IR (neat), ν(C=N) 1658 cm^{-1}; $[\alpha]_D^{24} = -115.8°$ ($c = 0.50$, $CHCl_3$); MS m/z 419. Anal. Calc. for $C_{23}H_{25}NOSFe$: C, 65.87; H, 6.01; N, 3.34. Found: C, 65.60; H, 6.07; N, 3.22%.

4.10. 1-[(S)-4-Phenyl-2,5-oxazolinyl]-1′-(phenylthio)-ferrocene (**5c**)

Compound **3c** (417 mg, 1.02 mmol) was allowed to react according to the procedures for **5a** to give 358 mg (0.815 mmol, 80%) of **5c** as a yellow solid, which could be recrystallized from hexane and a small amount of ether at −20°C: m.p. (dec.) = 80–81.5°C; ^{1}H-NMR δ 7.34 (m, 4H, Ph), 7.28 (m, 1H, Ph), 7.18 (m, 2H, Ph), 7.06 (m, 3H, Ph), 4.94 (m, 1H, Cp), 4.90 (m, 1H, Cp), 4.46 (m, 4H, Cp), 4.40 (t, $J = 1.8$ Hz, 2H, Cp), 5.27 (dd, $J_1 = 10.0$, $J_2 = 8.1$ Hz, 1H, =NC$\underline{H}$), 4.74 (dd, $J_1 = 10.0$, $J_2 = 8.3$ Hz, 1H, –OC$\underline{H}_2$), 4.22 (dd, $J_1 = 8.3$, $J_2 = 8.1$ Hz, 1H, –OC$\underline{H}_2$); ^{13}C-NMR δ 166.9 (–$\underline{C}$=N), 142.9, 140.5, 129.2, 129.1, 128.0, 127.2, 126.6, 125.5 (Ph), 78.1, 76.7, 76.6, 75.1, 72.5, 72.4, 72.2, 72.0, 71.1, 71.0, 70.5 (Cp, –O$\underline{C}$H$_2$, =N$\underline{C}$H); IR (neat) ν(C=N) 1651 cm^{-1}; $[\alpha]_D^{24} = -104.8°$ ($c = 0.5$, $CHCl_3$); MS m/z 439. Anal. Calc. for $C_{25}H_{21}NOSFe$: C, 68.34; H, 4.82; N, 3.19. Found: C, 68.16; H, 4.90; N, 2.94%.

4.11. [(**4a**)Pd(allyl)]Cl (**6a**)

[(η^3-C$_3$H$_5$)PdCl]$_2$ (10.3 mg, 0.028 mmol) and **4a** (27 mg, 0.056 mmol) were dissolved in CD_2Cl_2 (0.5 ml), and the resulting solution was stirred for 30 min at r.t. The solution was then transferred to a 5 mm NMR tube to obtain the NMR data: ^{1}H-NMR δ 7.56–7.38 (m, 10H, Ph), 5.66 (m, 1H, 2H of the allyl group), 4.77 (br s, 1H, Cp), 4.73 (br s, 1H, Cp), 4.72 (br s, 1H, 3H^s of the allyl group), 4.48 (br s, 4H, Cp), 4.45 (br s, 1H, Cp), 4.36 (br s, 1H, Cp), 4.29 (dd, $J_1 = 9.1$, $J_2 = 8.7$ Hz, 1H, –OC$\underline{H}_2$), 4.00 (dd, $J_1 = 8.1$, $J_2 = 8.0$ Hz, 1H, –OC$\underline{H}_2$), 3.90 (m, 1H, =NC$\underline{H}$), 3.79 (br s, 1H, 3H^a of the allyl group), 3.08 (br s, 2H, 1H^s and 1H^a of the allyl group), 1.74 (m, 1H, –C$\underline{H}$(CH$_3$)$_2$), 0.97 (d, $J = 6.7$ Hz, 3H, –CH(C$\underline{H}_3$)$_2$), 0.89 (d, $J = 6.7$ Hz, 3H, –CH(C$\underline{H}_3$)$_2$); ^{13}C-NMR δ 165.0 (–$\underline{C}$=N), 135.3 (d, $^1J_{C-P} = 8.8$ Hz, Ph), 134.7 (d, $^1J_{C-P} = 8.6$ Hz, Ph), 134.1 (d, $^2J_{C-P} = 10.0$ Hz, Ph), 133.9 (d, $^2J_{C-P} = 9.9$ Hz, Ph), 131.0 (d, $^3J_{C-P} = 2.0$ Hz, Ph), 130.9 (d, $^3J_{C-P} = 2.0$ Hz, Ph), 129.0, 128.9 (Ph), 118.5 (d, $J_{C-Pd-P} = 5.1$ Hz, 2C of the allyl group), 80.5 (br d, $J_{C-Pd-P} = 31.7$ Hz, 3C of the allyl group), 75.9, 75.8, 75.6, 75.4, 74.8, 75.5, 74.4, 73.6, 73.4, 73.3, 72.9, 72.7, 71.3 (Cp), 71.1 (=N$\underline{C}$H), 70.5 (–O$\underline{C}$H$_2$), 60.3 (1C of the allyl group), 33.3 (–$\underline{C}$H(CH$_3$)$_2$), 19.4 (–CH($\underline{C}$H$_3$)$_2$), 18.7 (–CH($\underline{C}$H$_3$)$_2$); ^{31}P-NMR δ 18.6.

4.12. [(**4b**)Pd(allyl)]Cl (**6b**)

According to the procedure for **6a**, the solution of **6b** was prepared from [(η^3-C$_3$H$_5$)PdCl]$_2$ (10.3 mg, 0.028 mmol) and **4b** (27.8 mg, 0.056 mmol): ^{1}H-NMR δ 7.62–7.32 (m, 10H, Ph), 5.66 (m, 1H, 2H of the allyl group), 4.75 (br s, 1H, Cp), 4.72 (br s, 1H, Cp), 4.72 (br s, 1H, 3H^s of the allyl group), 4.49 (br s, 5H, Cp), 4.38 (br s, 1H, Cp), 4.24 (dd, $J_1 = 10.0$, $J_2 = 8.7$ Hz, 1H, –OC$\underline{H}_2$), 4.09 (br dd, $J_1 = 7.9$, $J_2 = 7.6$ Hz, 1H, –OC$\underline{H}_2$), 3.86 (dd, $J_1 = 9.9$, $J_2 = 8.7$ Hz, 1H, 3H^a of the allyl group), 3.79 (dd, 1 $J_1 = 10.5$, $J_2 = 10.1$ Hz, 1H, =NC$\underline{H}$), 3.32 (br s, 1H, 1H^s of the allyl group), 2.85 (br d, $J = 11.8$ Hz, 1H, 1H^a of the allyl group), 0.90 (s, 9H, –C(C$\underline{H}_3$)$_3$); ^{13}C-NMR δ 164.6 (–$\underline{C}$=N), 134.9, 134.7, 134.0, 133.8, 133.6, 130.8, 130.7, 128.8, 128.7 (Ph), 118.2 (2C of the allyl group), 80.3 (br d, $J_{C-Pd-P} = 32.8$ Hz, 3C of the allyl group), 76.7, 76.0, 75.8, 75.5, 75.3, 75.2, 75.0, 74.7, 74.1, 74.0, 73.3, 73.2, 72.9, 71.1, 71.0 (Cp), 70.6 (=N$\underline{C}$H), 68.9 (–O$\underline{C}$H$_2$), 60.1(1C of the allyl group), 34.1 (–$\underline{C}$(CH$_3$)$_3$), 26.4 (–C($\underline{C}$H$_3$)$_3$); ^{31}P-NMR δ 18.6.

4.13. [(**4a**)Pd(1,3-diphenylallyl)]Cl (**7a**)

According to the procedure for **6a**, the solution of **7a** was prepared from [(η^3-1,3-diphenylallyl)PdCl]$_2$ (19 mg, 0.028 mmol) and **4a** (27 mg, 0.056 mmol): ^{1}H-NMR δ 7.80–6.80 (m, 20H, Ph), 6.41 (br dd, $J_1 = 11.8$, $J_2 = 11.7$ Hz, 1H, 2H of the allyl group), 5.63 (br d, $J = 9.0$ Hz, 1H, 3H^a of the allyl group), 4.90–4.10 (m, 9H, Cp and –OC$\underline{H}_2$), 4.47 (br s, 1H, 1H^a of the allyl group), 4.10–3.80 (m, 2H, –OC$\underline{H}_2$ and =NC$\underline{H}$), 1.76 (m, 1H, –C$\underline{H}$(CH$_3$)$_2$), 0.99 (d, $J = 6.6$ Hz, 3H, –CH(C$\underline{H}_3$)$_2$), 0.90 (d, $J = 6.6$ Hz, 3H, –CH(C$\underline{H}_3$)$_2$); ^{13}C-NMR δ 165.1 (–$\underline{C}$=N), 138.7, 137.3, 134.2, 134.1 , 133.9, 133.8, 133.6, 133.4, 133.3, 133.2, 130.3, 129.2, 129.0, 128.9, 128.6, 128.4, 127.9, 127.2 (Ph), 110.2 (br, 2C of the allyl group), 99.2 (br, 3 and C of the allyl group), 76.6 (=N$\underline{C}$H), 75.3, 74.1, 73.9, 73.6, 73.1, 72.5, 71.1, 71.0 (Cp), 73.5 (1 and C of the allyl group), 70.3 (–O$\underline{C}$H$_2$),

33.1 (–$\underline{C}$H(CH_3)$_2$), 19.2 (–CH($\underline{C}H_3$)$_2$), 18.5 (–CH($\underline{C}H_3$)$_2$); ^{31}P-NMR δ 22.8.

4.14. [(4b)Pd(1,3-diphenylallyl)]Cl (7b)

According to the procedure for **6a**, the solution of **7b** was prepared from [(η^3-1,3-diphenylallyl)PdCl]$_2$ (19 mg, 0.028 mmol) and **4a** (28 mg, 0.056 mmol): ^{1}H-NMR δ 7.80–6.80 (m, 20H, Ph), 6.38 (br dd, $J_1 = 13.0$, $J_2 =$ 11.0 Hz, 1H, 2H of the allyl group), 5.60 (br d, $J = 10.8$ Hz, 1H, 3H^a of the allyl group), 4.80–4.10 (m, 9H, Cp and –OC$\underline{H}_2$), 4.57 (br d, $J = 8.6$ Hz, 1H, 1H^a of the allyl group), 4.09 (dd, $J_1 = 8.4$, $J_2 = 8.3$ Hz, 1H, –OC$\underline{H}_2$), 3.86 (dd, $J_1 = 10.3$, $J_2 = 7.7$ Hz, =NC$\underline{H}$), 0.91 (s, 9H, –C(C$\underline{H}_3$)$_3$). ^{13}C-NMR δ 164.8 (–$\underline{C}$=N), 138.7, 137.4, 134.3, 134.1, 133.9, 138.7, 133.5, 133.3, 133.1, 132.7, 132.1, 131.7, 130.5, 130.4, 130.3, 130.1, 129.8, 129.4, 129.1, 129.0, 128.9, 128.6, 128.4, 128.2, 128.0, 127.2, 127.0, 126.8 (Ph), 110.3 (br, 2C of the allyl group), 98.9 (3C of the allyl group), 76.8 (=N$\underline{C}$H), 76.6, 76.3, 76.1, 76.0, 75.4, 75.3, 75.0, 74.9, 74.1, 74.0, 73.8, 73.6, 73.5, 73.4, 73.3, 73.2, 72.7, 71.1, 71.0, 70.6 (Cp), 73.6 (1C of the allyl group), 68.9 (–O$\underline{C}H_2$), 27.2 (–$\underline{C}$(CH_3)$_3$), 26.2 (–C($\underline{C}H_3$)$_3$); ^{31}P-NMR δ 22.9, 22.7.

4.15. General procedure for the Pd-catalyzed allylic alkylation

A mixture of (π-allyl) palladium chloride dimer (3.7 mg, 0.01 mmol) and a chiral ligand (0.02 mmol) in CH_2Cl_2 (1.7 ml) was stirred at 25°C for 30 min. This Pd-catalyst solution was added to (*E*)-1,3-diphenylprop-2-enyl acetate (252 mg, 1.0 mmol) in CH_2Cl_2 (1.7 ml). Then, dimethyl malonate (0.34 ml, 3.0 mmol), *N*,*O*-bis(trimethylsilyl)acetamide (0.74 ml, 3.0 mmol), and potassium acetate (2.0 mg, 0.02 mmol) were added sequentially. The reaction was monitored by TLC (4:1 hexane:ethyl acetate, $R_f = 0.4$). After the reaction was completed, the reaction mixture was diluted with CH_2Cl_2 (20 ml), washed with saturated aqueous NH_4Cl (15 ml), and dried over $MgSO_4$. The solvent was evaporated, and the resulting residue was chromatographed on silica gel (4:1 hexane:ethyl acetate). For the alkylated product, enantioselectivity was determined by HPLC with a chiral column (Chiralcel OD® 25 × 0.46 cm; 99:1 hexane:*i*-PrOH; flow rate = 0.9 ml min^{-1}; $t_R = 14.10$ (*R*), 15.44 (*S*) min).

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