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Chiral ferrocene-based phosphine-imine and sulfur-imine ligands for palladium-catalyzed asymmetric allylic alkylation of cycloalkenyl esters

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Abstract

Chiral ferrocene-based phosphine-imine ligands **1**–**3** and sulfur-imine ligand **4** were applied in the palladium-catalyzed asymmetric allylic alkylation of cycloalkenyl esters. The results revealed that the substitutents in aryl ring, ferrocenylmethyl and benzyliene position strongly affected the enantioselective induction of phosphine-imine ligands, and the most stereoselective ligand was ferrocenylphosphine-imine **1b** with a nitro group in the *meta*-position of phenyl ring. Under the optimized condition, up to 91% (enantiomeric excesses) e.e. of cyclic alkylation product was obtained by the use of **1b**.

Keywords: Ferrocene; Phosphine-imine ligands; Asymmetric; Allylic alkylation; Cycloalkenyl esters

1. Introduction

Palladium-catalyzed allylic substitutions have been one of the most intensely studied topics in asymmetric synthesis during the past two decades [1]. Specifically, various ligands have been successfully applied to the enantioselective alkylation of 1,3-diphenylprop-2-en-1-yl acetate [1,2]. As for the more preparatively particularly interesting and the more challenging cycloalkenyl ester substrates, few successful ligands have been reported. Therefore, the design and synthesis of new chiral ligands remains an important area of research for highly enantioselective alkylation of cycloalkenyl ester. A successful ligand should be readily accessible, stable, and highly tunable since the modification of the steric and electronic properties are often necessary for achieving high asymmetric induction. With the aim of meeting the above-mentioned requirements, a small quantity of diphosphine, phosphine-oxazoline, and phosphorus-sulfur ligands have been designed and applied in this reaction with good enantioselectivity recently (for examples of Pd-catalyzed asymmetric allylic alkylation of cycloalkenyl substrates, see: [3]). To the best of our knowledge, however, there are few report on the easily prepared and modified phosphine-Schiff base imine ligands for Pd-catalyzed asymmetric allylic alkylation of cycloalkenyl esters and no claim of the good enantioselectivity obtained with this kind of ligands [4], although very high enantioselectivity have been achieved in Pd-catalyzed alkylation of 1,3-diphenylprop-2-en-1-yl acetate with them (for examples of phosphine-imine ligands for Pd-catalyzed asymmetric allylic alkylation of 1,3-diphenylprop-2-en-1-yl esters, see: [5]). In the course of our work in the field of asymmetric synthesis [6], we have reported a series of readily accessible ferrocene-based phosphine-imine ligands **1**–**2** by the reaction of (*R*)-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine [(R,S_p)-PPFNH$_2$] with a variety of benzaldehydes and acetophenones, which were very effective ligands for Pd-catalyzed asymmetric alkylation of 1,3-diphenylprop-2-en-yl esters [6a,6d], as well as for Rh-catalyzed asymmetric hydrosilylation [6d,7]. In order to extend the validity of the ferrocenylphosphine-imine ligands **1**–**3** in asymmetric catalytic reaction, herein we wish to report the new use of these ligands and investigate the substitutent effect of phosphine-imine ligands in Pd-catalyzed asymmetric alkylation of cyclic allyl esters. As a result, an enantiomeric excesses (e.e.)-value of up to 91% e.e. was obtained in Pd-catalyzed asymmetric allylic alkylation of cyclic substrates by the use of ligand **1b** with a *meta*-NO_2 substitutent.

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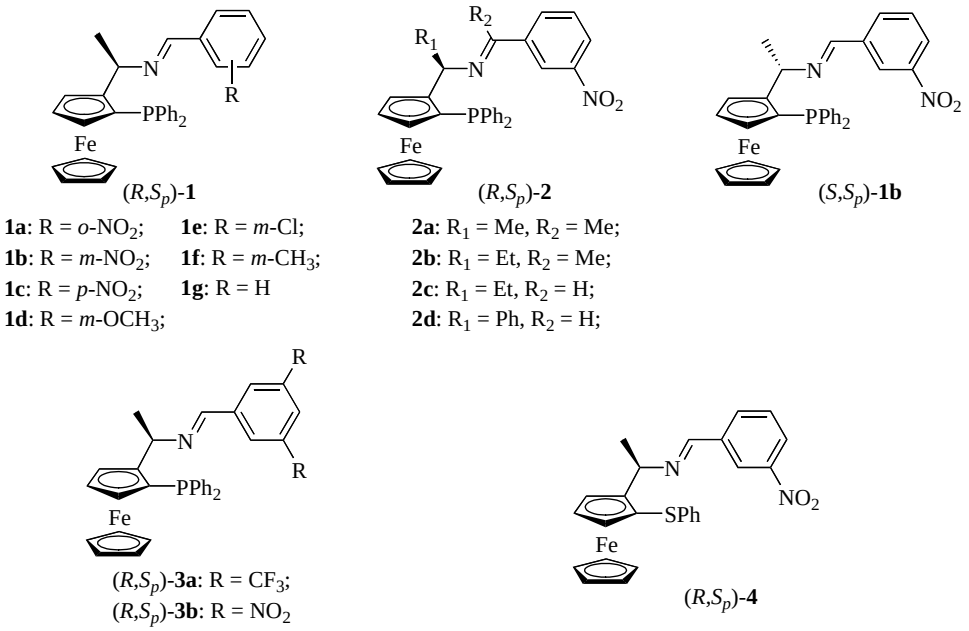


Fig. 1. Chemical structures of ligands **1**–**4**.

In addition, to compare the catalytic activity between *P*-imine and *S*-imine, the synthesis of ferrocenylsulfur-imine ligand **4** and its application in this reaction were also described (Fig. 1).

2. Experimental

2.1. General methods

Melting points were measured on a Yazawa micro melting point apparatus (uncorrected). Optical rotations were measured on a HORIBA SEPA-200 high sensitive polarimeter. The ^{1}H NMR spectra were recorded on a BRUKER DRX 400 system with TMS as an internal standard. The ^{31}P NMR spectra were recorded on a BRUKER DRX 400 system with 85% phosphoric acid as the external standard. The percentage of e.e. were determined by HPLC (Agilent 1100 series) analysis using a chiral β-390 stationary capillary column. All experiments were carried out under an argon atmosphere. All solvents were dried using standard procedures. Ferrocenylphosphine-imine ligands **1** and **2** were prepared according to our previously reported method [6a,6d]. Ligand **3a** was prepared by the use of Hayashi's procedure [7]. (*R*)-*N*,*N*-dimethyl-1-[(*S*)-2-(phenylthio)ferrocenyl]ethylamine **8** were synthesized following the literature method [8].

2.2. Synthesis of ferrocenylphosphine-imine ligands

2.2.1. Synthesis of (R)-N-(3-methylbenzylidene)-1-[(S)-2-(diphenylphosphino)ferrocenyl]ethylamine [(R,Sp)-1f]

To a solution of (R,S_p)-PPFNH$_2$ (413 mg, 1.0 mmol) in ethanol (8.0 ml) were added 3-methylbenzaldehyde (120 mg, 1.0 mmol) and anhydrous $MgSO_4$ (200 mg). The reaction mixture was then heated to reflux. After the reaction was complete (detected by TLC after 24 h), the reaction mixture was diluted with CH_2Cl_2·$MgSO_4$ were removed by filtration and the filtrate was concentrated under reduced pressure. The residue was purified by silica gel column chromatography modified by 2.0% of Et_3N (eluted by hexanes:ethyl acetate:Et_3N, 10:2:1) to afford the crude product. After recrystallized from *n*-hexane, 378 mg (73.4% yield) of the target compound **1f** as an orange solid was obtained. mp 139–140 °C; $[\alpha]_D^{25}$ −488 (c 0.31, CH_2Cl_2); ^{1}H NMR (DMSO-d^6) δ 1.67 (d, J = 6.4 Hz, 3H), 2.29 (s, 3H), 3.83 (s, 1H), 4.12 (s, 5H), 4.50 (s, 1H), 4.75 (s, 1H), 4.81–4.85 (m, 1H), 6.98–7.60 (m, 14H), 8.08 (s, 1H); ^{31}P NMR δ −24.7. HRMS calculated for $C_{32}H_{30}FeNP$ 515.1465, found 515.1461.

2.2.2. Synthesis of (S)-N-(3-nitrobenzylidene)-1-[(S)-2-(diphenylphosphino)ferrocenyl]ethylamine [(S,Sp)-1b]

Ferrocenylphosphine-imine (S,S_p)-**1b** was prepared as a foam solid in a way similar to that described for (R,S_p)-**1f** except for using (S,S_p)-PPFNH$_2$ instead of (R,S_p)-PPFNH$_2$, 3-nitrobenzaldehyde instead of 3-methylbenzaldehyde. $[\alpha]_D^{25}$ −42 (c 0.25, CH_2Cl_2); ^{1}H NMR (DMSO-d^6) δ 1.16 (d, J = 6.4 Hz, 3H), 3.84 (s, 1H), 4.00 (s, 5H), 4.48 (s, 1H), 4.75–4.77 (m, 2H), 7.25–7.64 (m, 10H), 7.88–7.92 (m, 1H), 8.40–8.45 (m, 2H), 8.78 (s, 1H), 8.83 (s, 1H); ^{31}P NMR δ −25.1. HRMS calculated for $C_{31}H_{26}FeN_3O_4P$ 591.1010, found 591.1001.

2.2.3. Synthesis of (R)-N-(3,5-dinitrobenzylidene)-1-[(S)-2-(diphenylphosphino)ferrocenyl]ethylamine [(R,Sp)-3b]

Ferrocenylphosphine-imine (R,S_p)-**3b** was prepared as a darken red solid in a way similar to that described for

(R,S_p)-**1f** except for using 3,5-dinitrobenzaldehyde instead of 3-methylbenzaldehyde. mp 137–138 °C; $[\alpha]_D^{25}$ −468 (c 0.26, CH_2Cl_2); ^{1}H NMR (DMSO-d^6) δ 1.60 (d, J = 6.4 Hz, 3H), 3.64 (s, 1H), 4.10 (s, 5H), 4.41 (s, 1H), 4.71 (s, 1H), 4.90–4.92 (m, 1H), 6.62–6.66 (m, 1H), 6.79–6.89 (m, 4H), 7.39–7.42 (m, 5H), 8.32 (s, 3H), 8.74 (s, 1H); ^{31}P NMR δ −23.1. HRMS calculated for $C_{31}H_{26}FeN_3O_4P$ 591.1010, found 591.1001.

2.3. Synthesis of (R)-N-[1-(3-nitrophenyl)methylidene]-1-[(S)-2-(phenylthio)ferrocenyl]ethylamine [(R,S$_p$)-4]

2.3.1. Synthesis of (R)-1-[(S)-2-(phenylthio)ferrocenyl]-ethylamine [(R,S$_p$)-10]

To a solution of (*R*)-*N*,*N*-dimethyl-1-[(*S*)-2-(phenylthio)-ferrocenyl]ethylamine **8** (3.65 g, 10 mmol) in 25 ml of CH_2Cl_2 at 0 °C was dropwisely added MeI (1.25 ml, 2.84 g, 20 mmol). After the addition was complete, the solution was allowed to warm slowly to room temperature. After the reaction was complete (detected by TLC), all of the volatiles were removed under reduced pressure to afford 4.81 g (94.9% yield) of ammonium salt **9**. To ammonium salt **9** (1.40 g, 2.68 mmol) was added a solution of 10 ml 25% aqueous NH_3 in 20 ml of CH_3CN (8.0 ml). The mixture was then placed in a 100 ml autoclave and heated at 70–80 °C overnight. The mixture was diluted with 10 ml of CH_2Cl_2, and then all of the volatiles were removed under reduced pressure. The resulting residue was purified by column chromatography on a silica gel column modified by 2.0% of Et_3N (eluted by hexanes:ethyl acetate:Et_3N, 20:1:0.1–8:1:0.1–4:1:0.1) to afford 0.65 g (72.0% yield) of (*R*)-1-[(*S*)-2-(phenylthio)ferrocenyl]ethylamine (**10**) as a brown viscous liquid. ^{1}H NMR ($CDCl_3$) δ 1.43 (d, J = 6.8 Hz, 3H), 4.11–4.16 (m, 1H), 4.21 (s, 5H), 4.31–4.32 (m, 1H), 4.38 (s, 1H), 4.45 (s, 1H), 7.01–7.06 (m, 3H), 7.14–7.18 (m, 2H).

2.3.2. Synthesis of (R)-N-[1-(3-nitrophenyl)methylidene]-1-[(S)-2-(phenylthio)ferrocenyl]ethylamine [(R,S$_p$)-4]

To a solution of (*R*)-1-[(*S*)-2-(phenylthio)ferrocenyl]-ethylamine **10** (337 mg, 1.0 mmol) in ethanol (8.0 ml) were added 3-nitrobenzaldehyde (151 mg, 1.0 mmol) and anhydrous $MgSO_4$ (400 mg). The reaction mixture was refluxed overnight under argon atmosphere. After cooled to room temperature, the mixture was diluted with CH_2Cl_2·$MgSO_4$ were removed by filtration and the filtrate was concentrated under reduced pressure. The residue was purified by column chromatography on a silica gel column modified by 2.0% of Et_3N (eluted by hexanes:ethyl acetate:Et_3N, 10:1:0.1) to afford the crude product. After recrystallized from *n*-hexane, 312 mg (66.4% yield) of (*R*)-*N*-[1-(3-nitrophenyl)methylidene]-1-[(*S*)-2-(phenylthio)ferrocenyl]ethylamine **4** as an orange crystalline was obtained. mp 148–149 °C; $[\alpha]_D^{25}$ −232 (c 0.30, CH_2Cl_2); ^{1}H NMR (DMSO-d^6) δ 1.60 (d, J = 6.4 Hz, 3H), 4.30 (s, 5H), 4.49 (s, 1H), 4.50 (s, 1H), 4.69 (s, 1H), 4.70–4.72 (m, 1H), 6.48–6.51 (m, 1H), 6.71–6.77 (m, 4H), 7.47–7.51 (m, 1H), 7.61–7.63 (m, 1H), 7.89 (s, 1H), 8.07 (s, 1H), 8.12–8.14 (m, 1H). HRMS calculated for $C_{25}H_{22}FeN_2O_2S$ 470.0751, found 470.0745.

2.4. General procedure for Pd-catalyzed asymmetric alkylation of cycloalkenyl esters 5

A solution of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (3.7 mg, 0.01 mmol) and chiral ferrocenylphosphine-imine **1**–**3** or sulfur-imine **4** (0.025 mmol) in toluene (1.5 ml) was stirred at room temperature for 1 h under argon atmosphere. To this Pd-catalyst was added cycloalkenyl esters **5** (0.50 mmol) in toluene (1.5 ml), followed by dimethyl malonate (170 ul, 1.5 mmol) or diethyl methylmalonate (260 ul, 1.5 mmol), *N*,*O*-bis(trimethylsilyl)acetamide (BSA, 0.37 ml, 1.5 mmol), and a catalytic amount of LiOAc (0.01 mmol) sequentially. After stirring for 24 h at room temperature, the reaction mixture was quenched with saturated aqueous NH_4Cl solution and diluted with CH_2Cl_2. The organic layer was separated, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was purified by column chromatography on a silica gel column (eluted by hexanes:ethyl acetate, 20:1) to afford the pure product **7**, e.e.-value for **7** was determined by GC (β-390 stationary capillary column). The absolute configuration was determined by the specific rotation with a literature value [9].

3. Results and discussion

3.1. Substituent effect of ferrocenylphosphine-imine ligands on the palladium-catalyzed asymmetric allylic alkylation of cyclohexenyl acetate 5a with dimethyl malonate 6a

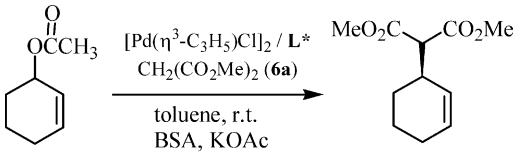
Initially, the substitutent effect of ferrocenylphosphine-imine ligands on the Pd-catalyzed asymmetric allylic alkylation of cyclohexenyl acetate **5a** with dimethyl malonate **6a** was examined (Eq. (1)). The reaction was carried out in toluene at room temperature in the presence of 2.0 mol% of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$, 5.0 mol% of chiral ligand, and a mixture of *N*,*O*-bis(trimethylsilyl)acetamide and 2.0 mol% of potassium acetate. The results were summarized in Table 1. The data indicated that the substitutent in ferrocenylphosphine-imine skeleton strongly affected the catalytic activity and enantioselectivity. Firstly, the effect of substitutent in aryl ring was investigated (entries 1–7). The position of the substitutent in phenyl ring had great effect in the catalytic reaction, and ligand with a *meta*-substitutent tended to exhibit better enantioselectivity (entries 1–3). Thus, ligand **1a** with an *ortho*-NO_2 substitutent gave the allylic alkylation product with only 32% yield and 59% e.e. (entry 1). However, if the NO_2 group was in *meta*-position of phenyl ring, a significant increase of the catalytic activity and enantioselectivity was observed and the reaction

Table 1
Pd-catalyzed asymmetric allylic alkylation of cyclohexenyl acetate **5a** using ferrocenylphosphine-imine ligands **1**–**3**[a]

Entry	Ligand	Yield (%)[b]	e.e. (%)[c] (Configuration)[d]
1	(R,S_p)-**1a**	32	59 (*R*)
2	(R,S_p)-**1b**	81	83 (*R*)
3	(R,S_p)-**1c**	80	76 (*R*)
4	(R,S_p)-**1d**	82	67 (*R*)
5	(R,S_p)-**1e**	43	65 (*R*)
6	(R,S_p)-**1f**	61	66 (*R*)
7	(R,S_p)-**1g**	48	63 (*R*)
8	(R,S_p)-**2a**	95	62 (*R*)
9	(R,S_p)-**2b**	91	61 (*R*)
10	(R,S_p)-**2c**	90	77 (*R*)
11	(R,S_p)-**2d**	37	68 (*R*)
12	(R,S_p)-**3a**	<10	73 (*R*)
13	(R,S_p)-**3b**	No reaction	N.D. (*R*)
14	(S,S_p)-**1b**	33	42 (*R*)

[a] The reactions were carried out in toluene in the present of 2.0 mol% $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$, 5.0 mol% of chiral ligand, 3.0 eq. of dimethyl malonate, 3.0 eq. of BSA and 2.0 mol% of KOAc at room temperature for 24 h.
[b] Isolated yields.
[c] Determined by GC analysis using a chiral β-390 stationary capillary column.
[d] The *R*-configuration was confirmed by comparing the specific rotation with a literature value [9].

gave allylic product with 81% yield and 83% e.e. (entry 2). Comparing to ligand **1b**, ligand **1c** with *para*-NO_2 group exhibited the slightly lower enantioselectivity and catalytic activity (entry 3 versus entry 2). Changing the substitutent in *meta*-position of phenyl ring resulted in the dramatic change of the reactivity and enantioselectivity, and all of the *meta*-substituted ligands **1d**–**1g** gave the allylic product with lower enantioselectivity than the corresponding *meta*-NO_2 substituted analogue (entries 4–7 versus entry 2). We next investigated the influence of substitutent in benzylidene and ferrocenylmethyl position on the catalytic reaction, and found that introducing an ethyl group into ferrocenylmethyl position or introducing a methyl group into benzylidene position resulted in the remarkable increase of the catalytic activity and the observable decrease of the enantioselectivity (entries 8–10). However, a phenyl group in ferrocenylmethyl position caused the dramatic decrease of the reactivity and enantioselectivity (entry 11). Due to the good result obtained by the use of **1b** with a *meta*-NO_2 substitutent, we then speculated that ligand **3** with two electron-withdrawing substitutents was perhaps more effective ligands for this reaction. However, the results were proved to be very discouraged. Using 3,5-dinitro substituted ligand **3b**, no allylic alkylation product was obtained (entry 13), while 3,5-bis(trifluoromethyl) substituted ligand **3a** only gave the allylic product in <10% yield with 73% e.e. (entry 12). The absolute configuration of product **7a** from these reactions was proven to be *R* by comparing the specific rotation with a literature value [9].

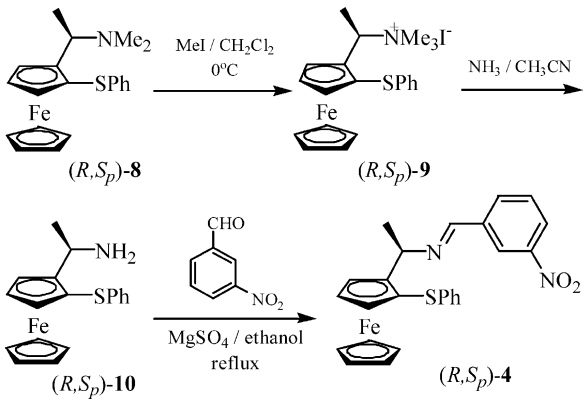


(1)

In order to investigate the diastereomeric effect of ferrocenylphosphine-imine ligands in the catalytic reaction, (S,S_p)-**1b** was synthesized and applied to the model reaction. Comparing to its (R,S_p)-analogue, (S,S_p)-**1b** gave the allylic product with lower yield and enantioselectivity but having the same configuration (entry 14 versus entry 2). This result suggested that (*R*)-central chirality and (S_p)-planar chirality in these ferrocenylphosphine-imine ligands was matched for this reaction.

3.2. Ferrocenylsulfur-imine ligand for the palladium-catalyzed asymmetric alkylation of cyclohexenyl acetate with dimethyl malonate

The easy derivativation of the ferrocene skeleton stimulated us to synthesize ferrocenylsulfur-imine analogues to make a comparison between *P*-imine and *S*-imine in the catalytic activity. Ferrocenylsulfur-imine ligand **4** was easily synthesized according to the procedure outlined in Scheme 1. The initial step in the synthesis involved the methylation of (*R*)-*N*,*N*-dimethyl-1-[(*S*)-2-(phenylthio)ferrocenyl]ethylamine **8** with MeI to generate an ammonium salt **9** [8b]. Subsequent treatment of ammonium salt **9** with NH_3 gave (*R*)-1-[(*S*)-2-(phenylthio)ferrocenyl]ethylamine **10** in 72.0% yield [10]. Treatment of **10** with 3-nitrobenzaldehyde in ethanol in the presence of $MgSO_4$ at refluxing temperature gave *S*-imine **4** in 66.4% yield. The ferrocenylsulfur-imine **4** was then applied to the palladium-catalyzed asymmetric allylic alkylation of cyclohexenyl acetate **5a** under the above-described conditions. Comparing to the corresponding phosphine-imine analogue, the rate of reaction intervened by sulfur-imine **4** was very slow, even after 7 days, only 32% yield of allylic product was obtained, although a good enantioselectivity (82% e.e.) was achieved.



Scheme 1. Synthesis of *S*,*N*-ligand (R,S_p)-**4**.

Table 2
Pd-catalyzed asymmetric alkylation of cycloalkenyl esters using ferrocenylphosphine-imine ligand **1b**[a]

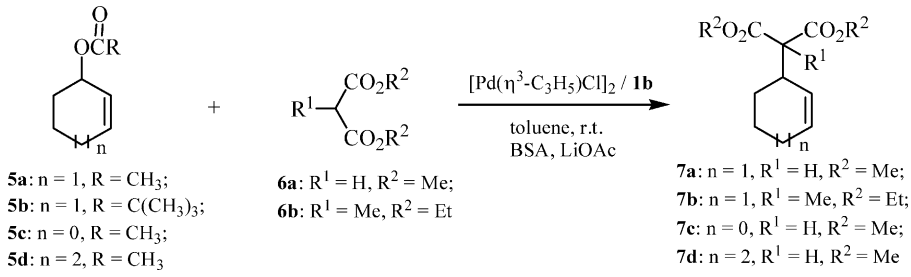
Entry	Substrate	Nucleophile	Base	Solvent	Temperature(°C)	Yield (%)[b]	% e.e.[c] (Configuration)[d]
1	**5a**	**6a**	BSA–CsOAc	Toluene	25	91	82 (*R*)
2	**5a**	**6a**	BSA–KOAc	Toluene	25	81	83 (*R*)
3	**5a**	**6a**	BSA–NaOAc	Toluene	25	94	86 (*R*)
4	**5a**	**6a**	BSA–LiOAc	Toluene	25	96	86 (*R*)
5	**5a**	**6a**	BSA–LiOAc	CH_2Cl_2	25	90	70 (*R*)
6	**5a**	**6a**	BSA–LiOAc	Ether	25	63	71 (*R*)
7	**5a**	**6a**	BSA–LiOAc	THF	25	23	73 (*R*)
8	**5b**	**6a**	BSA–LiOAc	Toluene	25	76	89 (*R*)
9	**5a**	**6a**	BSA–LiOAc	Toluene	10	91	90 (*R*)[e]
10	**5a**	**6a**	BSA–LiOAc	Toluene	0	47	91 (*R*)[e]
11	**5a**	**6b**	BSA–LiOAc	Toluene	25	78	81(*R*)
12	**5c**	**6a**	BSA–LiOAc	Toluene	25	89	82 (*R*)
13	**5d**	**6a**	BSA–LiOAc	Toluene	25	95	89 (*R*)

[a] The reactions were carried out in the presence of 2.0 mol% $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$, 5.0 mol% of chiral ligand, 3.0 eq. of dimethyl malonate or diethyl methylmalonate, 3.0 eq. of BSA and 2.0 mol% of metal acetate at room temperature for 24 h.
[b] Isolated yields.
[c] Determined by GC analysis using a β-390 stationary capillary column.
[d] The *R*-configuration was confirmed by comparing the specific rotation with a literature value [9].
[e] The reaction was carried out for 48 h.

3.3. Pd-catalyzed asymmetric allylic alkylation of cycloalkenyl esters by the use of (R,S_p)-*1b*

The above results revealed that the most stereoselective ligand was ferrocenylphosphine-imine **1b** with a nitro group in *meta*-position of phenyl ring. We then used this ligand to carry out the following research. Optimization of the reaction conditions was first performed, and the results were summarized in Table 2. The metal acetate had important influence in the catalytic reaction. Using CsOAc as the additive gave the allylic product with slightly lower enantioselectivity but higher yield comparing to that using KOAc (entry 1 versus entry 2). Upon use of NaOAc or LiOAc instead of KOAc, the yield increased observably and the enantioselectivity was raised to 86% e.e. (entries 3 and 4). The effect of solvents on this reaction was also investigated and a significant variation in the catalytic activity was observed. Using CH_2Cl_2 as solvent, the reaction gave the product with the similar reactivity but lower enantioselectivity to that using toluene as solvent (entry 5). However, using Et_2O as solvent slowed down the reaction rate dramatically, only 63% yield with 71% e.e. of allylic product was obtained (entry 6). THF proved to be an inferior solvent for this reaction. When the reaction carried out in this solvent, only 23% yield and 73% e.e. of allylic product was obtained (entry 7). Replacing acetate **5a** with pivalate **5b** as substrate resulted in a slight increase of enantioselectivity to 89% e.e. and a marked drop of yield to 76% (entry 8). When the reaction temperature was lowered to 10 °C, an increase of the enantioselectivity to 90% e.e. was obtained but longer time was required to complete the reaction (entry 9). Lowering the reaction temperature to 0 °C could further improve the enantioselectivity to 91% e.e. but decrease the reaction rate dramatically (entry 10).

To extend the validity of ferrocenylphosphine-imine ligand in this enantioselective reaction, the applications of **1b** for other substrates or nucleophiles were then examined. The cyclohexenyl acetate **5a** underwent alkylation with diethyl methylmalonate **6b** to give allylic product **7b** in 78% yield and 81% e.e. (entry 11). The alkylation of cyclopentenyl pivalate **5c** gave 82% ee of **7c** in 89% yield (entry 12), and an e.e.-value of 89% e.e. with 95% yield was observed in the alkylation of the cycloheptenyl acetate **5d** (entry 13).



5a: n = 1, R = CH_3;
5b: n = 1, R = $C(CH_3)_3$;
5c: n = 0, R = CH_3;
5d: n = 2, R = CH_3

6a: R^1 = H, R^2 = Me;
6b: R^1 = Me, R^2 = Et

7a: n = 1, R^1 = H, R^2 = Me;
7b: n = 1, R^1 = Me, R^2 = Et;
7c: n = 0, R^1 = H, R^2 = Me;
7d: n = 2, R^1 = H, R^2 = Me

(2)

4. Summary

In summary, we have reported the new use of ferrocenylphosphine-imine ligands **1**–**3** and sulfur-imine **4** in the asymmetric catalysis and found ligand **1b** with a nitro group in *meta*-position of phenyl ring was effective for Pd-catalyzed asymmetric allylic alkylation of acyclic and cyclic substrates. In this paper, an e.e.-value of 91% for cyclic alkylation product was achieved.

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References

[1] (a) B.M. Trost, P.E. Strege, J. Am. Chem. Soc. 99 (1977) 1649;
(b) B.M. Trost, D.L. Van Vranken, Chem. Rev. 96 (1996) 395;
(c) I. Ojima (Ed.), Catalytic Asymmetric Synthesis, VCH, New York, 1999.

[2] (a) G. Helmchen, J. Organomet. Chem. 576 (1999) 203;
(b) F. Fache, E. Schulz, M.L. Tommasino, M. Lemaire, Chem. Rev. 100 (2000) 2159;
(c) T. Hayashi, Acc. Chem. Res. 33 (2000) 354;
(d) G. Helmchen, A. Pfaltz, Acc. Chem. Res. 33 (2000) 336;
(d) L.-X. Dai, T. Tu, S.-L. You, W.-P. Deng, X.-L. Hou, Acc. Chem. Res. 36 (2003) 659;
(e) O.B. Sutcliffe, M.R. Bryce, Tetrahedron: Asymmetry 14 (2003) 2297;
(f) G. Chelucci, G. Orru, G.A. Pinna, Tetrahedron 59 (2003) 9471.

[3] (a) B.M. Trost, R.C. Bunt, J. Am. Chem. Soc. 116 (1994) 4089;
(b) G. Knuhl, P. Sennhenn, G. Helmchen, J. Chem. Soc., Chem. Commun. 1995 1845;
(c) T. Minami, Y. Okada, T. Otaguro, S. Tawaraya, T. Furuichi, T. Okauchi, Tetrahedron: Asymmetry 6 (1995) 2469;
(d) B.M. Trost, R.C. Bunt, Angew. Chem. Int. Ed. Engl. 35 (1996) 99;
(e) T. Nishimata, M. Mori, J. Organomet Chem. 63 (1998) 7586;
(f) S. Kudis, G. Helmchen, Angew. Chem. Int. Ed. 37 (1998) 3047;
(g) P. Dierkes, S. Ramdeehul, L. Barloy, A.D. Cian, J. Fischer, P.C.J. Kamer, P.W.N.M. van Leeuwen, J.A. Osborn, Angew. Chem. Int. Ed. 37 (1998) 3116;
(h) S.R. Gilbertson, D. Xie, Angew. Chem. Int. Ed. 38 (1999) 2750;
(i) A. Saitoh, T. Uda, T. Morimoto, Tetrahedron: Asymmetry 10 (1999) 4501;
(j) D.A. Evans, K.R. Campos, J.S. Tedrow, F.E. Michael, M.R. Gagne, J. Am. Chem. Soc. 122 (2000) 7905;
(k) J.M. Longmire, B. Wang, X. Zhang, Tetrahedron Lett. 41 (2000) 5435;
(l) D.-R. Hou, J.H. Reibenspies, K. Burgess, J. Organomet Chem. 66 (2001) 206;
(m) Y. Hamada, K. Sakaguchi, K. Hatano, O. Hara, Tetrahedron Lett. 42 (2001) 1297;
(n) S.-L. You, Y.-M. Luo, W.-P. Deng, X.-L. Hou, L.-X. Dai, J. Organomet. Chem. 637–639 (2001) 845;
(o) L. Xiao, W. Weissensteiner, K. Mereiter, M. Widhalm, J. Organomet Chem. 67 (2002) 2206;
(p) K. Shibatomi, Y. Uozumi, Tetrahedron: Asymmetry 13 (2002) 1769.

[4] A. Saitoh, K. Achiwa, K. Tanaka, T. Morimoto, J. Organomet Chem. 65 (2000) 4227.

[5] (a) Y. Suzuki, Y. Ogata, K. Hiroi, Tetrahedron: Asymmetry 10 (1999) 1219;
(b) H.-Y. Jang, H. Seo, J.W. Han, Y.K. Chung, Tetrahedron Lett. 41 (2000) 5083;
(c) T. Kohara, Y. Hashimoto, K. Saigo, Synlett 4 (2000) 517;
(d) M.T. Reetz, G. Haderlein, K. Angermund, J. Am. Chem. Soc. 122 (2000) 996;
(e) T. Fukuda, A. Takehara, M. Iwao, Tetrahedron: Asymmetry 12 (2001) 2793;
(f) H.-J. Park, J.W. Han, H. Seo, H.-Y. Jang, Y.K. Chung, J. Suh, J. Mol. Catal. A: Chem. 174 (2001) 151;
(g) J.H. Lee, S.U. Son, Y.K. Chung, Tetrahedron: Asymmetry 14 (2003) 2109.

[6] (a) X. Hu, H. Dai, X. Hu, H. Chen, J. Wang, C. Bai, Z. Zheng, Tetrahedron: Asymmetry 13 (2002) 1687;
(b) X. Hu, H. Chen, X. Hu, H. Dai, C. Bai, J. Wang, Z. Zheng, Tetrahedron Lett. 43 (2002) 9179;
(c) X. Hu, H. Chen, H. Dai, X. Hu, Z. Zheng, Tetrahedron: Asymmetry 14 (2003) 2073;
(d) X. Hu, H. Chen, H. Dai, Z. Zheng, Tetrahedron: Asymmetry 14 (2003) 3415;
(e) X. Hu, H. Chen, H. Dai, X. Hu, Z. Zheng, Chin. Chem. Lett. 14 (2003) 1113;
(f) X. Hu, H. Dai, C. Bai, H. Chen, Z. Zheng, Tetrahedron: Asymmetry 15 (2004) 1065;
(g) H. Dai, X. Hu, H. Chen, C. Bai, Z. Zheng, J. Mol. Catal. A: Chem. 209 (2004) 19;
(h) H. Dai, X. Hu, H. Chen, C. Bai, Z. Zheng, J. Mol. Catal. A: Chem. 211 (2004) 17.

[7] T. Hayashi, C. Hayashi, Y. Uozumi, Tetrahedron: Asymmetry 6 (1995) 2503.

[8] (a) M.O. Okoroafor, D.L. Ward, C.H. Brubaker, Organometallics 7 (1988) 1504;
(b) H. Seo, H. Park, B.Y. Kim, J.H. Lee, S.U. Son, Y.K. Chung, Organometallics 22 (2003) 618.

[9] P. Sennhenn, B. Gabler, G. Helmchen, Tetrahedron Lett. 35 (1994) 8598.

[10] T. Tu, Y.-G. Zhou, X.-L. Hou, L.-X. Dai, X.-C. Dong, Y.-H. Yu, J. Sun, Organometallics 22 (2003) 1255.