Tetrahedron: *Asymmetry* 21 (2010) 2050–2054

Contents lists available at ScienceDirect

Tetrahedron: *Asymmetry*

journal homepage: www.elsevier.com/locate/tetasy

Pd(II)-catalyzed and diethylzinc-mediated asymmetric umpolung allylation of aldehydes in the presence of chiral phosphine-Schiff base type ligands

Jia-Jun Jiang [a], De Wang [a], Wen-Feng Wang [a], Zhi-Liang Yuan [a], Mei-Xin Zhao [a], Fei-Jun Wang [a], Min Shi [a,b,*]

[a] *Key Laboratory for Advanced Materials and Institute of Fine Chemicals, School of Chemistry & Molecular Engineering, East China University of Science and Technology, 130 Mei Long Lu, Shanghai 200 237, China*

[b] *State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 354 Fenglin Lu, Shanghai 200 032, China*

ARTICLE INFO

Article history:
Received 9 June 2010
Accepted 29 June 2010
Available online 24 July 2010

ABSTRACT

Chiral phosphine-Schiff base type ligand **L3** prepared from (*R*)-(−)-2-(diphenylphosphino)-1,1′-binaphthyl-2′-amine was found to be a fairly effective chiral ligand for the Pd(II)-catalyzed and diethylzinc-mediated enantioselective umpolung allylation of aldehydes to give homoallylic alcohols in good yields, moderate enantioselectivities and high *syn* diastereoselectivities.

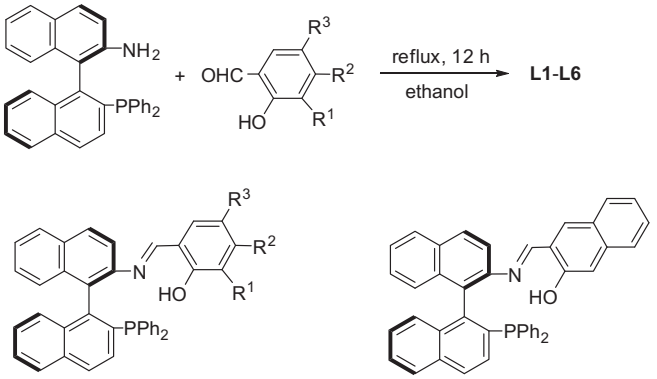
1. Introduction

Catalytic asymmetric synthesis provides chemists with new and powerful tools for the efficient synthesis of complex molecules. Amongst the many suitable reactions, the asymmetric allylic alkylation (AAA) reaction is a very attractive and powerful synthetic strategy, as it enables the direct and stereocontrolled formation of stereogenic centers bearing a range of functionalities available for further structural elaboration.[1] Since an initial publication concerning umpolung allylation by Brown et al. in 1987,[2] Tamaru et al. have effectively demonstrated that the latent reactivity of the π-allyl palladium complex can be reversed from electrophilic to nucleophilic in the presence of Et_2Zn or Et_3B.[3] The umpolung of the π-allyl palladium complexes has provided a versatile allylation method for aldehydes and ketones via nucleophilic metal-coordinated allylic moieties. The first π-allyl palladium complexes and diethylzinc-mediated enantioselective catalytic umpolung allylation were reported by Zanoni et al. in 2004.[4] Following this pioneering work, Feringa et al.[5a] and Hou et al.[5b] provided further examples of this reaction in the presence of diethylzinc by using chiral monodentate phosphoramidite and planar chiral [2,2]paracyclophane monophosphine ligands, respectively. Recently, our group reported the first example of axially chiral bis(NHC)-Pd(II) complex-catalyzed and Et_2Zn-mediated enantioselective umpolung allylation of aldehydes with cyclohex-2-enyl acetate.[5c] On the other hand, Zhou et al. developed an analogous Et_3B-mediated version of this umpolung allylation by using a chiral spiro-monodentate phospholane ligand, which is complementary to the diethylzinc-mediated methodology.[5d]

Recently, we explored the phosphine-Schiff base-Pd(II)-catalyzed asymmetric allylic alkylation. Herein, we demonstrate that these catalysts can also be used to effect diethylzinc-mediated enantioselective umpolung allylation of aldehydes.

2. Results and discussion

Chiral phosphine-Schiff base type ligands **L1**–**L6**[6] were synthesized from the reaction of salicylaldehydes as well as its analogues with (*R*)-(−)-2-(diphenylphosphino)-1,1′-binaphthyl- 2′-amine[7] in absolute ethanol at reflux for 12 h, respectively. After the usual workup, these ligands were obtained in good yields (Scheme 1).



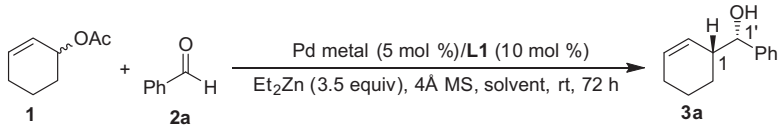
L1: R^1 = H, R^2 = H, R^3 = H
L2: R^1 = ^{t}Bu, R^2 = H, R^3 = ^{t}Bu
L3: R^1 = Cl, R^2 = H, R^3 = Cl
L4: R^1 = H, R^2 = H, R^3 = Me
L5: R^1 = H, R^2 = OMe, R^3 = H

Scheme 1. Preparation of phosphine-Schiff base type ligands **L1**–**L6**.

* Corresponding author.
E-mail address: Mshi@mail.sioc.ac.cn (M. Shi).

0957-4166/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2010.06.039

Table 1
Optimization of the reaction conditions in the asymmetric umpolung allylation of cyclohex-2-enyl acetate **1** and benzaldehyde **2a**



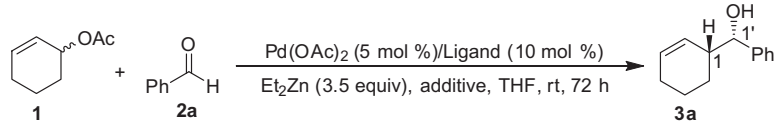
Entry[a]	Solvent	Pd metal	Yield[b] (%)	*syn*:*anti*[c]	ee[d] (%)
1	THF	$Pd(PhCN)_2Cl_2$	51	>30:1	20 (1*R*, 1′*S*)
2	THF	$[(\eta^3\text{-}C_3H_5PdCl)_2]$	13	>30:1	20 (1*R*, 1′*S*)
3	THF	$Pd(MeCN)_2Cl_2$	46	>30:1	35 (1*R*, 1′*S*)
4	THF	$Pd(OAc)_2$	16	>30:1	53 (1*R*, 1′*S*)
5	THF	Pd_2dba_3	54	>30:1	30 (1*R*, 1′*S*)
6[e]	THF	$Pd(OAc)_2$	51	>30:1	24 (1*R*, 1′*S*)
7	Toluene	$Pd(OAc)_2$	20	>30:1	33 (1*R*, 1′*S*)
8	CH_2Cl_2	$Pd(OAc)_2$	14	>30:1	23 (1*R*, 1′*S*)

[a] All reactions were performed using **1** (0.24 mmol), **2a** (0.2 mmol), Pd metal (0.01 mmol), **L1** (0.02 mmol), 4 Å MS (50 mg) and Et_2Zn (0.7 mmol) in 1.0 mL of solvent at rt for 72 h.
[b] Isolated yield.
[c] Determined by ^1H NMR analysis.
[d] Determined by chiral HPLC analysis.
[e] 5.0 equiv of Et_2Zn was added.

Initial examination using cyclohex-2-enyl acetate **1** and benzaldehyde **2a** as the substrates in the presence of a chiral phosphine-Schiff base type ligand **L1** (10 mol %) combined with various palladium sources (5 mol %) was aimed at determining the optimal conditions; the results of these experiments are summarized in Table 1. We found that by using tetrahydrofuran (THF) as a solvent and 4 Å MS (50 mg) as an additive, the corresponding product **3a** could be obtained in moderate yields with a variety of palladium sources at room temperature. Up to 53% ee was achieved using $Pd(OAc)_2$ as the palladium source with high *syn*-selectivity (*syn*:*anti* >30:1), albeit in only 13% yield (Table 1, entries 1–5). The absolute configuration of the adduct was assigned by comparison of the specific rotation with that from the literature.[5a] By screening various solvents such as toluene and CH_2Cl_2, we found that THF was the best solvent (Table 1, entries 4, 7 and 8). Furthermore, an attempt to increase the amount of the Et_2Zn reagent led to higher yield but lower enantioselectivity (Table 1, entry 6).

With these optimized conditions in hand, we next attempted to examine various chiral phosphine-Schiff base type ligands **L1**–**L6** in this asymmetric reaction. The results are summarized in Table 2. From the ligands screened, **L3**, bearing an electron-withdrawing group on the benzene ring, was the best chiral phosphine-Schiff base type ligand for this asymmetric umpolung allylation, affording product **3a** in 65% ee and 41% yield at room temperature for 72 h (Table 2, entries 1–6). In addition, an electron-donating group on the benzene ring such as chiral phosphine-salen type ligands **L2**, **L4** and **L5** gave the product **3a** in moderate ees (10–40% ee) and moderate yields (Table 2, entries 2, 4 and 5). These results suggested that the substituent on the benzene ring in the chiral phosphine-Schiff base type ligands played a very important role in chiral induction in this asymmetric umpolung allylation. Elevating the reaction temperature resulted in a decrease in the yield as well as the ee of the product **3a** (Table 2, entry 7). In the absence of 4 Å MS, the yield of the product **3a** could be slightly improved upon

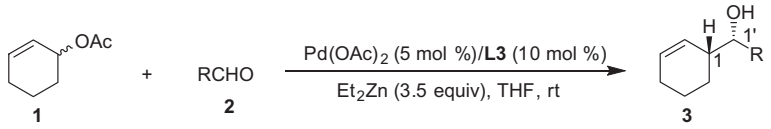
Table 2
Optimization of the reaction conditions in the asymmetric umpolung allylation of cyclohex-2-enyl acetate **1** and benzaldehyde **2a**



Entry[a]	Additive	Ligand	Yield[b] (%)	*syn*:*anti*[c]	ee[d] (%)
1	4 Å MS	**L1**	16	>30:1	53 (1*R*, 1′*S*)
2	4 Å MS	**L2**	32	28:1	40 (1*S*, 1′*R*)
3	4 Å MS	**L3**	41	>30:1	65 (1*R*, 1′*S*)
4	4 Å MS	**L4**	43	26:1	35 (1*R*, 1′*S*)
5	4 Å MS	**L5**	32	>30:1	10 (1*R*, 1′*S*)
6	4 Å MS	**L6**	32	>30:1	8 (1*R*, 1′*S*)
7[e]	4 Å MS	**L3**	20	>30:1	53 (1*R*, 1′*S*)
8	—	**L3**	46	>30:1	66 (1*R*, 1′*S*)
9[f]	—	**L3**	27	>30:1	65 (1*R*, 1′*S*)
10[g]	—	**L3**	62	>30:1	66 (1*R*, 1′*S*)

[a] All reactions were performed using **1** (0.24 mmol), **2a** (0.2 mmol), $Pd(OAc)_2$ (0.01 mmol), ligand (0.02 mmol), additive (50 mg) and Et_2Zn (0.7 mmol) in 1.0 mL of THF at rt for 72 h.
[b] Isolated yield.
[c] Determined by ^1H NMR analysis.
[d] Determined by chiral HPLC analysis.
[e] The reaction was performed at 50 °C.
[f] Compounds **1** (0.2 mmol) and **2a** (0.24 mmol) were used.
[g] Compounds **1** (0.4 mmol) and **2a** (0.2 mmol) were used.

Table 3
Asymmetric umpolung allylation of cyclohex-2-enyl acetate **1** and aldehydes **2** under the optimal conditions



1 2 3

Entry[a]	R	*t* (h)	Yield[b] (%)	*syn*:*anti*[c]	ee[d] (%)
1	C_6H_5 (**2a**)	72	**3a**, 62	>30:1	66 (1*R*, 1′*S*)
2	2-ClC_6H_4 (**2b**)	48	**3b**, 79	>30:1	68 (1*R*, 1′*S*)
3	3-ClC_6H_4 (**2c**)	48	**3c**, 88	>30:1	66 (1*R*, 1′*S*)
4	4-ClC_6H_4 (**2d**)	48	**3d**, 68	>30:1	64 (1*R*, 1′*S*)
5	4-FC_6H_4 (**2e**)	48	**3e**, 68	>30:1	46 (1*R*, 1′*S*)
6	4-$CF_3C_6H_4$ (**2f**)	48	**3f**, 82	>30:1	67 (1*R*, 1′*S*)
7	2,4-$Cl_2C_6H_3$ (**2g**)	48	**3g**, 94	>30:1	62 (1*R*, 1′*S*)
8	4-$CH_3C_6H_4$ (**2h**)	72	**3h**, 25	>30:1	37 (1*R*, 1′*S*)
9	1-Np (**2i**)	72	**3i**, 46	>30:1	47 (1*R*, 1′*S*)

[a] All reactions were performed using **1** (0.4 mmol), **2** (0.2 mmol), $Pd(OAc)_2$ (0.01 mmol), **L3** (0.02 mmol) and Et_2Zn (0.7 mmol) in 1.0 mL of THF at rt.
[b] Isolated yield.
[c] Determined by ^1H NMR analysis.
[d] Determined by chiral HPLC analysis.

without the loss of ee under identical conditions (Table 2, entry 8). Furthermore, we found that increasing the amount of **1** provided product **3a** in higher yield (Table 2, entries 9 and 10).

Therefore, the best reaction conditions were to carry out the reaction in THF using $Pd(OAc)_2$ (5 mol %) as the palladium source and being diethylzinc mediated in the presence of phosphine-Schiff base type ligand **L3** (10 mol %) at room temperature.

With these optimal reaction conditions in hand, a series of aldehydes **2b**–**2i** with various substituents on the aromatic scaffold were used to further explore the substrate scope (Table 3). For all of the substrates, the reactions demonstrated excellent diastereoselectivities. It was found that for substrates **2b**–**2g** bearing an electron-withdrawing group on the benzene ring, the corresponding products **3b**–**3g** were obtained in moderate enantioselectivities (46–68% ee) and good yields (68–94%) (Table 3, entries 2–7). Substrate **2h** with an electron-donating group on the benzene ring also produced the product **3h** in 37% ee, albeit in 25% yield (Table 3, entry 8). Similarly, 1-naphthaldehyde **2i** produced the product **3i** in 47% ee and 46% yield in this asymmetric umpolung allylation (Table 3, entry 8).

3. Conclusion

In conclusion, chiral phosphine-Schiff base type ligand **L3**, which was prepared from (*R*)-2-(diphenylphosphino)-1,1′-binaphthyl-2′-amine was found to be a fairly effective chiral ligand for the Pd(II)-catalyzed and Et_2Zn-mediated asymmetric umpolung allylation of aldehydes with cyclohex-2-enyl acetate, giving the corresponding products in good yields, moderate enantioselectivities and high *syn* diastereoselectivities under mild conditions. These results will prompt us to design and synthesize more new effective chiral phosphine-Schiff base type ligands for asymmetric reactions. Efforts are currently underway to elucidate the mechanistic details of this asymmetric umpolung allylation of aldehydes with cyclohex-2-enyl acetate and to disclose the exact structure of the active species in this catalytic system.

4. Experimental

4.1. General methods

Melting points were obtained with a Yanagimoto micro melting point apparatus and are uncorrected. Optical rotations were determined in a solution of $CHCl_3$ at 20 °C by using a Perkin-Elmer-241 MC polarimeter; $[\alpha]_D$-values are given in units of 10^{-1} deg cm^2 g^{-1}. Infra-red spectra were measured on a spectrometer. The ^1H NMR spectra and ^{13}C NMR spectra were recorded on a Bruker AM-300 spectrometer for solution in $CDCl_3$ with tetramethylsilane (TMS) as an internal standard. Mass spectra were recorded with a HP-5989 instrument and HRMS was measured by a Finnigan MA+ mass spectrometer. Organic solvents used were dried by standard methods when necessary. Commercially obtained reagents were used without further purification. All reactions were monitored by TLC with Huanghai GF_{254} silica gel coated plates. Flash column chromatography was carried out using 300–400 mesh silica gel at increased pressure. All reactions were performed under argon using standard Schlenk techniques. Chiral HPLC was performed by using a SHIMADZU SPD-10A vp series instrument with chiral columns (Chiralpak AS-H, AD-H columns, ϕ 4.6 × 250 mm, Daicel Chemical Co. Ltd) and the absolute configuration of the major enantiomer was assigned according to the sign of the specific rotation.

Chiral phosphine-Schiff base type ligands **L1**–**L6** were prepared according to our previously reported procedure.[6f]

4.2. General procedure for the catalytic asymmetric umpolung allylation of aldehydes with cyclohex-2-enyl acetate

To a Schlenk tube of ligand **L3** (12.5 mg, 0.02 mmol) in THF (1.0 mL) was added $Pd(OAc)_2$ (2.3 mg, 0.01 mmol), and the resulting solution was stirred at room temperature for 30 min. The reaction tube was then allowed to cool down to 0 °C for another 15 min. Finally, aldehydes **2** (0.2 mmol) and Et_2Zn (1.0 M in hexanes, 0.7 mmol, 0.7 mL) were added to the solution, followed by the addition of the cyclohex-2-enyl acetate **1** (0.4 mmol) and the resulting mixture was stirred for 48–72 h at room temperature. After completion of the reaction, saturated aqueous NH_4Cl solution was added to quench the reaction. The aqueous layer was extracted with CH_2Cl_2. The combined organic layers were washed with brine. After drying over anhydrous Na_2SO_4, the solvent was removed under reduced pressure. Further purification of the residue was performed by flash column chromatography on SiO_2 (PE/EtOAc = 20:1) to give the pure product **3**. The ee of the product **3** was determined by chiral HPLC analysis.

4.2.1. (1*R*,1′*S*)-(Cyclohex-2-enyl)(phenyl)methanol 3a

A colourless oil. Yield: 62%. This is a known compound.[5c] ^1H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.46–1.55 (m, 2H), 1.68–1.77 (m,

2H), 1.98 (br, 3H), 2.50 (br, 1H), 4.57 (d, J = 6.6 Hz, 1H), 5.36–5.39 (m, 1H), 5.79–5.83 (m, 1H), 7.25–7.34 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$, TMS) δ 21.1, 23.8, 25.2, 42.9, 77.3, 126.5, 127.4, 128.0, 128.2, 130.3, 142.8. Enantiomeric excess was determined by HPLC with a Chiralcel AS-H column (hexane/*i*PrOH = 99:1, 0.7 mL/min, 214 nm, t_{minor} = 18.64 min, t_{major} = 22.92 min; $[\alpha]_D^{20}$ = +11 (*c* 1.0, C_6H_6), 66% ee.

4.2.2. (1*R*,1′*S*)-(2-Chlorophenyl)(cyclohex-2-enyl)methanol 3b

A colourless oil. Yield: 79%. This is a known compound.[5c] ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.43–1.57 (m, 3H), 1.74–1.80 (m, 1H), 2.00 (br, 3H), 2.65–2.68 (m, 1H), 5.10 (d, J = 6.6 Hz, 1H), 5.49 (m, 1H), 5.87–5.92 (m, 1H), 7.17–7.34 (m, 3H), 7.55 (d, J = 6.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, TMS) δ 21.3, 22.8, 25.1, 40.7, 73.2, 126.6, 128.0, 128.17, 128.24, 129.3, 131.0, 132.0, 139.9. Enantiomeric excess was determined by HPLC with a Chiralcel AS-H column (hexane/*i*PrOH = 99:1, 0.7 mL/min, 214 nm, t_{minor} = 11.96 min, t_{major} = 14.71 min; $[\alpha]_D^{20}$ = −24 (*c* 1.6, $CHCl_3$), 68% ee.

4.2.3. (1*R*,1′*S*)-(3-Chlorophenyl)(cyclohex-2-enyl)methanol 3c

A colourless oil. Yield: 88%. This is a known compound.[5c] ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.45–1.55 (m, 2H), 1.58–1.79 (m, 2H), 1.98 (br, 2H), 2.07 (s, 1H), 2.45–2.47 (m, 1H), 4.57 (d, J = 6.3 Hz, 1H), 5.36–5.40 (m, 1H), 5.82–5.88 (m, 1H), 7.18–7.29 (m, 3H), 7.34 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, TMS) δ 21.0, 23.4, 25.1, 42.9, 76.5, 124.6, 126.6, 127.4, 127.5, 129.4, 131.0, 134.1, 144.9. Enantiomeric excess was determined by HPLC with a Chiralcel AS-H column (hexane/*i*PrOH = 99:1, 0.7 mL/min, 214 nm, t_{minor} = 15.12 min, t_{major} = 16.71 min; $[\alpha]_D^{20}$ = +7 (*c* 1.7, $CHCl_3$), 66% ee.

4.2.4. (1*R*,1′*S*)-(4-Chlorophenyl)(cyclohex-2-enyl)methanol 3d

A colourless oil. Yield: 68%. This is a known compound.[5c] ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.45–1.56 (m, 2H), 1.63–1.77 (m, 2H), 1.97 (br, 3H), 2.45–2.47 (m, 1H), 4.58 (d, J = 6.0 Hz, 1H), 5.36–5.40 (m, 1H), 5.81–5.87 (m, 1H), 7.25–7.33 (m, 4H). Enantiomeric excess was determined by HPLC with a Chiralcel AD-H column (hexane/*i*PrOH = 99:1, 0.7 mL/min, 214 nm, t_{minor} = 25.71 min, t_{major} = 27.79 min; $[\alpha]_D^{20}$ = +5 (*c* 1.4, $CHCl_3$), 64% ee.

4.2.5. (1*R*,1′*S*)-(Cyclohex-2-enyl)(4-fluorophenyl)methanol 3e

A colourless oil. Yield: 68%. ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.43–1.57 (m, 2H), 1.64–1.81 (m, 2H), 1.93–1.99 (m, 3H), 2.42–2.50 (m, 1H), 4.57–4.59 (m, 1H), 5.35–5.39 (m, 1H), 5.80–5.86 (m, 1H), 7.00–7.06 (m, 2H), 7.26–7.33 (m, 2H). ^{13}C NMR ($CDCl_3$, TMS, 75 MHz) δ 21.0, 23.7, 25.2, 43.0 (d, J = 1.1 Hz), 76.7, 115.0 (d, J = 21.2 Hz), 127.6, 128.0 (d, J = 7.7 Hz), 130.7, 138.5 (d, J = 3.4 Hz), 162.0 (d, J = 243.6 Hz). ^{19}F NMR (282 MHz, $CDCl_3$, CF_3CO_2H) δ −115.4. IR (CH_2Cl_2) ν 3391, 3023, 2927, 2861, 1604, 1510, 1223, 1156, 839 cm^{-1}. MS (ESI) m/z 205 (M^+−H). HRMS (ESI) calcd for $C_{13}H_{14}FO$: 205.1029, found: 205.1024. Enantiomeric excess was determined by HPLC with a Chiralcel AD-H column (hexane/*i*PrOH = 95:5, 0.7 mL/min, 214 nm, t_{minor} = 12.54 min, t_{major} = 13.74 min; $[\alpha]_D^{20}$ = +4 (*c* 1.2, $CHCl_3$), 46% ee.

4.2.6. (1*R*,1′*S*)-(Cyclohex-2-enyl)(4-(trifluoromethyl)phenyl)-methanol 3f

A colourless oil. Yield: 82%. This is a known compound.[5c] ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.44–1.62 (m, 3H), 1.68–1.78 (m, 1H), 1.99–2.05 (m, 3H), 2.46–2.52 (m, 1H), 4.68 (d, J = 5.7 Hz, 1H), 5.38–5.42 (m, 1H), 5.84–5.90 (m, 1H), 7.44 (d, J = 8.1 Hz, 2H), 7.59 (d, J = 8.1 Hz, 2H); ^{19}F NMR (282 MHz, $CDCl_3$, CF_3CO_2H) δ −68.0. Enantiomeric excess was determined by HPLC with a Chiralcel AD-H column (hexane/*i*PrOH = 99:1, 0.7 mL/min, 214 nm, t_{minor} = 19.54 min, t_{major} = 21.96 min; $[\alpha]_D^{20}$ = +1 (*c* 1.8, $CHCl_3$), 67% ee.

4.2.7. (1*R*, 1′*S*)-(Cyclohex-2-enyl)(2,4-dichlorophenyl)methanol 3g

A colourless oil. Yield: 94%. ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.39–1.52 (m, 3H), 1.68–1.77 (m, 1H), 1.99–2.04 (m, 2H) 2.07–2.11 (m, 1H), 2.63 (br, 1H), 5.05–5.06 (m, 1H), 5.50 (m, 1H) 5.90–5.94 (m, 1H) 7.24–7.27 (m, 1H), 7.34 (s, 1H), 7.48–7.51 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$, TMS) δ 21.2, 22.6, 25.1, 40.7, 72.7, 126.9, 127.6, 129.0, 129.2, 131.5, 132.5, 133.2, 138.5; IR (CH_2Cl_2) ν 3408, 2931, 1770, 1590, 1561, 1470, 1383, 1250, 1103, 1077 cm^{-1}. MS (ESI) m/z 255 (M^+−H). HRMS (ESI) calcd for $C_{13}H_{13}Cl_2O$: 255.0343, found: 255.0341. Enantiomeric excess was determined by HPLC with a Chiralcel AD-H column (hexane/*i*PrOH = 100:1, 0.7 mL/min, 214 nm, t_{minor} = 29.37 min, t_{major} = 35.04 min; $[\alpha]_D^{20}$ = −22 (*c* 2.2, $CHCl_3$), 62% ee.

4.2.8. (1*R*, 1′*S*)-(Cyclohex-2-enyl)(*p*-tolyl)methanol 3h

A colourless oil. Yield: 25%. This is a known compound.[5c] ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) ^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ 1.43–1.54 (m, 2H), 1.65–1.76 (m, 2H), 1.88 (br, 1H), 1.97 (br, 2H), 2.34 (s, 3H), 2.47–2.48 (m, 1H), 4.52 (d, J = 6.6 Hz, 1H), 5.34–5.38 (m, 1H), 5.76–5.81 (m, 1H), 7.13–7.16 (m, 2H), 7.21–7.25 (m, 2H). Enantiomeric excess was determined by HPLC with a Chiralcel AS-H column (hexane/*i*PrOH = 99:1, 0.7 mL/min, 214 nm, t_{minor} = 12.54 min, t_{major} = 16.87 min; $[\alpha]_D^{20}$ = +5 (*c* 0.5, $CHCl_3$), 37% ee.

4.2.9. (1*R*, 1′*S*)-(Cyclohex-2-enyl)(naphthalen-1-yl)methanol 3i

A colourless oil. Yield: 46%. This is a known compound.[5c] ^{1}H NMR ($CDCl_3$, TMS, 300 MHz) δ 1.42–1.63 (m, 3H), 1.73–1.78 (m, 1H), 1.99–2.07 (m, 3H), 2.74–2.78 (m, 1H), 5.42 (d, J = 5.1 Hz, 1H), 5.47–5.50 (m, 1H), 5.82–5.87 (m, 1H), 7.45–7.51 (m, 3H), 7.67 (d, J = 7.2 Hz, 1H), 7.77 (d, J = 9.0 Hz, 1H), 7.84–7.88 (m, 1H), 8.02–8.05 (m, 1H). Enantiomeric excess was determined by HPLC with a Chiralcel AD-H column (hexane/*i*PrOH = 95:5, 0.7 mL/min, 230 nm, t_{major} = 27.17 min, t_{minor} = 34.97 min; $[\alpha]_D^{20}$ = −27 (*c* 0.8, $CHCl_3$), 47% ee.

Acknowledgements

Financial support from the Shanghai Municipal Committee of Science and Technology (08dj1400100-2), National Basic Research Program of China (973)-2010CB833302, and the National Natural Science Foundation of China (20902019, 20872162, 20672127, 20821002, 20732008, 20772030 and 20702059) is greatly acknowledged.

References

1. (a) Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395–422; (b) Trost, B. M.; Lee, C. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; Wiley-VCH: Weinheim, Germany, 2000; pp 593–649; (c) Graening, T.; Schmalz, H. G. *Angew. Chem., Int. Ed.* **2003**, *42*, 2580–2584; (d) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921–2944.
2. Brown, H. C.; Bhat, K. S.; Randad, R. S. *J. Org. Chem.* **1987**, *52*, 3701–3702.
3. (a) Kimura, M.; Shimizu, M.; Shibata, K.; Tazoe, M.; Tamaru, Y. *Angew. Chem., Int. Ed.* **2003**, *42*, 3392–3395; (b) Tamaru, Y. In *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E., Ed.; Wiley-Interscience: New York, 2002; pp 1917–1943; (c) Kimura, M.; Tomizawa, T.; Horino, Y.; Tanaka, S.; Tamaru, Y. *Tetrahedron Lett.* **2000**, *41*, 3627–3629; (d) Tamaru, Y. *J. Organomet. Chem.* **1999**, *576*, 215–231; (e) Yasui, K.; Goto, Y.; Yajima, T.; Taniseki, Y.; Fugami, K.; Tanaka, A.; Tamaru, Y. *Tetrahedron Lett.* **1993**, *34*, 7619–7622.
4. Zanoni, G.; Gladiali, S.; Marchetti, A.; Piccinini, P.; Tredici, I.; Vidari, G. *Angew. Chem., Int. Ed.* **2004**, *43*, 846–849.
5. (a) Howell, G. P.; Minnaard, A. J.; Feringa, B. L. *Org. Biomol. Chem.* **2006**, *4*, 1278–1283; (b) Zhang, T.-Z.; Dai, L.-X.; Hou, X.-L. *Tetrahedron: Asymmetry* **2007**, *18*, 251–259; (c) Wang, W.-F.; Zhang, T.; Shi, M. *Organometallics* **2009**, *28*, 2640–2642; (d) Zhu, S.-F.; Yang, Y.; Wang, L.-X.; Liu, B.; Zhou, Q.-L. *Org. Lett.* **2005**, *7*, 2333–2335.
6. (a) For related chiral phosphine and imino ligands. See: Zhang, X.-M. PCT Int. Appl. Coden: PLXXD2 WO 2001000581, 2001, 93 p.; (b) Hu, X.-Q.; Chen, H.-L.; Zhang, X.-M. *Angew. Chem., Int. Ed.* **1999**, *38*, 3518–3521; (c) Brunner, H.; Henning, F.; Webe, M. *Tetrahedron: Asymmetry* **2002**, *13*, 37–42; (d) Stoop, R. M.;

Bachmann, S.; Valentini, M.; Mezzetti, A. *Organometallics* **2000**, *19*, 4117–4126; (e) Gao, J.-X.; Zhang, H.; Yi, X.-D.; Xu, P.-P.; Tang, C.-L.; Wan, H.-L.; Tsai, K. R.; Ikariya, T. *Chirality* **2000**, *12*, 383–388; (f) Jiang, J.-J.; Shi, M. *Tetrahedron: Asymmetry* **2007**, *18*, 1376–1382.

7. (a) Sumi, K.; Ikariya, T.; Noyori, R. *Can. J. Chem.* **2000**, *78*, 697–703; (b) Botman, P. N. M.; David, O.; Amore, A.; Dinkelaar, J.; Vlaar, M. T.; Goubitz, K.; Fraanje, J.; Schenk, H.; Hiemstra, H.; van Maarseveen, J. H. *Angew. Chem., Int. Ed.* **2004**, *43*, 3471–3473.