Tetrahedron: *Asymmetry* 22 (2011) 929–935

Contents lists available at ScienceDirect

Tetrahedron: *Asymmetry*

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

Enantioselective nitroaldol reaction catalyzed by chiral C_1-tetrahydro-1,1′-bisisoquinoline–copper(I) complexes

Yao Qiong Ji, Gao Qi, Zaher M. A. Judeh *

School of Chemical and Biomedical Engineering, Nanyang Technological University, 62 Nanyang Drive, N1.2 B1-14, Singapore 637459, Singapore

ARTICLE INFO

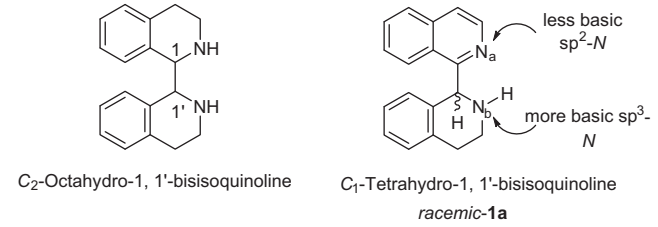
Article history:
Received 22 February 2011
Accepted 19 May 2011

ABSTRACT

An efficient catalytic system comprising of chiral C_1-tetrahydro-1,1′-bisisoquinoline and CuCl in the ratio of 2:1 has been developed for the enantioselective Henry reaction. The catalytic efficiencies of the chiral C_1-tetrahydro-1,1′-bisisoquinolines are governed to a great extent by the structural constraints and the type of substituent on the sp^3-*N*. Aromatic and aliphatic aldehydes reacted with nitromethane to give β-nitroalcohols in very high yields (up to 95%) and enantioselectivities (up to 91% ee). The present catalyst system is simple in operation since no special precautions were taken to exclude moisture or air from the reaction flask and no additives were required for activation. Nonlinear effects have also been studied for this reaction.

1. Introduction

The design, synthesis and application of chiral ligands are significant tasks in asymmetric catalysis. The use of chiral C_2-1,1′-bisisoquinolines (Fig. 1) in various asymmetric reactions resulted in poor to modest enantioselectivities.[1] We have recently disclosed a straightforward synthesis of the C_1-tetrahydro-1,1′-bisisoquinoline framework and observed major structural differences between the C_1-tetrahydro-1,1′-bisisoquinolines and the C_2-octahydro-1,1′-bisisoquinolines (Fig. 1) with the help of X-ray crystallographic analysis.[2] Potentially, the C_1-tetrahydro-1,1′-bisisoquinolines present structurally robust motifs amenable to stereoelectronic tuning and optimization and are envisioned to catalyze a wide array of asymmetric reactions. Indeed, application of C_1-tetrahydro-1,1′-bisisoquinoline (*R*)-**1a** in the enantioselective addition of Et_2Zn to various aldehydes gave exciting results.[2b] We decided to further explore and broaden the application of the new chiral C_1-tetrahydro-1,1′-bisisoquinolines by examining their efficiencies in the enantioselective Henry reaction. Practically, the enantiopure nitroalcohol adducts obtained from this reaction can be transformed into many valuable chiral building blocks such as nitro alkenes, aminoalcohols and aminoacids among others.[3] Due to its significance, the development of catalysts for the enantioselective Henry reaction has been escalating since Shibasaki's first seminal report.[4] The majority of the successful catalysts reported are copper complexes of chiral nitrogen ligands such as bisoxazolines,[5] bisimidazolines,[6] (−)-sparteine,[7] diamines,[8] iminopyridines,[9] aminopyridines,[9] tetrahydrosalens[10] and *N*,*N*′-dioxides,[11] guanidine–thiourea.[12] Nevertheless, other complexes such as Co-salens,[13] Zn-aminoalcohols,[14a] Zn-azacrowns,[14b,c] Cr-salens[15] and rare-earth-BINOLs[4,16] have been employed with variable success.



C_2-Octahydro-1, 1'-bisisoquinoline

C_1-Tetrahydro-1, 1'-bisisoquinoline
racemic-**1a**

Figure 1. General structures of C_2-octahydro-1,1′-bisisoquinoline, C_1-tetrahydro-1,1′-bisisoquinoline and *rac*-**1a**.

Herein, we report on the application of chiral C_1-tetrahydro-1,1′-bisisoquinolines (*R*)-**1a**–**f** (Fig. 2) as ligands for the enantioselective Henry reaction and examine the effects of the substituents attached to the sp^3-*N* on the reactivity and selectivity.

2. Results and discussion

Racemic C_1-tetrahydro-1,1′-bisisoquinoline *rac*-**1a** was readily synthesized under the Bischler–Napieralski conditions and resolved using (*S*)-(+)-α-methylbenzyl isocyanate to give (*R*)-**1a** (Fig. 2).[2a] C_1-Tetrahydro-1,1′-bisisoquinoline (*R*)-**1a** demonstrates diverse stereoelectronic features: (i) it coordinates to metals through a strongly basic sp^3-*N* atom and a weekly basic sp^2-*N* atom;[5a] (ii) it has a constrained structure whereby the sp^2-*N* containing ring is flat[17] due to its aromaticity while the sp^3-*N* containing ring assumes a twist-boat conformation[2b–d,17] (note: the nitrogens

* Corresponding author. Fax: +65 67947553.
E-mail address: zaher@ntu.edu.sg (Z.M.A. Judeh).

0957-4166/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2011.05.013

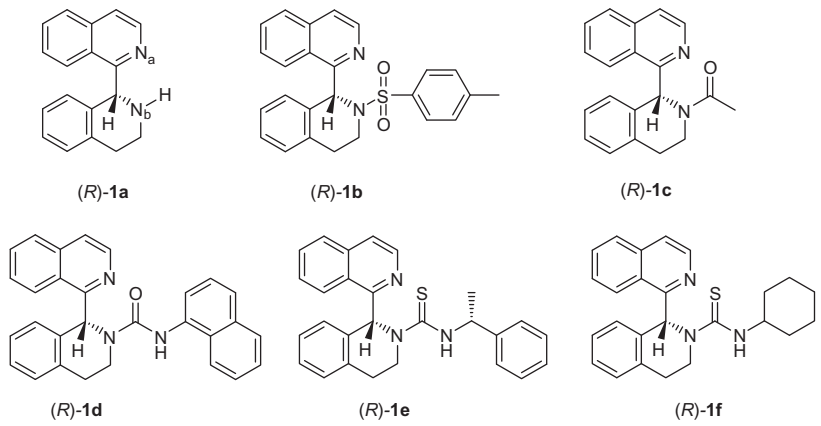
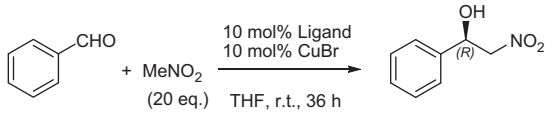


Figure 2. Chiral C_1-tetrahydro-1,1′-bisisoquinolines (*R*)-**1a**–**f**.

in C_2-1,1′-bisisoquinolines (Fig. 1) are both sp^3 hybridized and both heterocyclic rings assume a twist-boat conformation.[2b–d,17]); (iii) it can be easily functionalized at the sp^3-*N* (i.e., N_b) to bring further contrasting Lewis acidity effects to the metal center. In the Henry reaction, the Lewis acidity of the metal center is proven to play an important role in activating the aldehyde and has tremendous impact on the enantioinduction.[5a] Thus, treatment of (*R*)-**1a** with *p*-toluenesulfonyl chloride, acetyl chloride, 1-naphthyl isocyanate, (*S*)-(−)-(α)-methylbenzyl isothiocyanate and cyclohexyl isothiocyanate provided ligands (*R*)-**1b**–**f**, respectively, in excellent yields (Fig. 2).[2a] The substituents at sp^3-*N* of ligands (*R*)-**1b**–**f** were chosen to provide variable steric bulk and electronic effects at the metal center.

We started our investigation by employing ligands (*R*)-**1a**–**1f** in a standard enantioselective addition of nitromethane to benzaldehyde **2a** to examine their effectiveness as chiral inducers (Table 1). Therefore, the Henry reaction was performed using a combination of 10 mol % ligand, 10 mol % CuBr and 20 equiv $MeNO_2$ in THF at rt. Ligand (*R*)-**1a** gave β-nitroalcohol (*R*)-**3a** in excellent 94% yield and in moderate 68% ee (Table 1, entry 1). Unexpectedly, ligands (*R*)-**1b**–**d** gave no products and the starting benzaldehyde **2a** was recovered back unchanged (Table 1, entries 2–4). This lack of reactivity may be attributed to the ineffective formation of the required copper complexes. Interestingly, ligand (*R*)-**1e** gave (*R*)-**3a** in 30% yield and 24% ee (Table 1, entry 5). To ensure that the induction is due to the C1′ chiral carbon and not due to the chirality of the (*S*)-(−)-(α)-methylbenzyl substituent, ligand (*R*)-**1f** was employed (Table 1, entry 6). Again, the product (*R*)-**3a** was obtained in 20% yield and 21% ee (Table 1, entry 6). To confirm that the catalysis observed in entries 5 and 6 (Table 1) is due to the copper complex with (*R*)-**1e** and (*R*)-**1f**, we repeated the reaction under exactly the same conditions with the exception that CuBr was not used. In these cases, the starting material was recovered unchanged and no products were formed indicating that (*R*)-**1e** and (*R*)-**1f** are unable to catalyze the reaction without CuBr. Further insights on the reactivity come from the preferential conformations deduced from X-ray crystallographic analysis of these ligands although the conformation in the solid and solution states could be different to some extent. In the case of (*R*)-**1a**, copper could easily chelate to the *syn*-oriented[2b] nitrogens (N_a and N_b) to form chiral complexes since there is no impedance resulting from the low steric hindrance brought by the H group at N_b. On the contrary, similar copper complexes could not be obtained in the case of (*R*)-**1b** and (*R*)-**1c** due to the extreme crowding brought about by the bulky *p*-toluenesulfonyl and acetyl substituents as evidenced from the X-ray structure. Thus, bulky substituents at N_b cause severe crowding at the chelating nitrogens and force them to adapt an *anti* conformation preventing effective chelation and the formation of useful metal complexes.

Table 1
Asymmetric Henry reaction using ligands (*R*)-**1a**–**f**[a]



2a **3a**

Entry	Ligand	Yield[b] (%)	ee[c] (%)
1	(*R*)-**1a**	94	68
2	(*R*)-**1b**	0	—
3	(*R*)-**1c**	0	—
4	(*R*)-**1d**	0	—
5	(*R*)-**1e**	30	24
6	(*R*)-**1f**	20	21

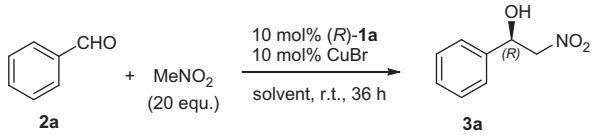
[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde **2a** in the presence of ligand (10 mol %) and CuBr (10 mol %) using $MeNO_2$ (20 equiv) in THF (1.5 ml) at rt for 36 h.
[b] Yields of isolated products.
[c] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H column. The absolute configuration (*R*) was determined by comparison with the literature values.[8d]

Ligand (*R*)-**1a** was used for further optimization of the reaction conditions. The effects of various protic and aprotic solvents (Table 2) were examined under the reaction conditions used in Table 1. Generally, aprotic solvents (Table 2, entries 3–13) were found to be superior to protic solvents (Table 2, entries 1 and 2) in terms of yields and enantioselectivities of **3a**. Among the aprotic solvents, $ClCH_2CH_2Cl$ gave the best enantioselectivity (77% ee) *albeit* in a low 45% yield. Generally, ether-type solvents gave high yields and moderate enantioselectivities (Table 2, entries 8–13). Based on the above results, further optimizations were explored using $ClCH_2CH_2Cl$ as the solvent of choice.

Next, the effects of various copper sources were examined (Table 3). Copper(I) (Table 3, entries 1–3) showed clear superiority compared to copper(II) sources (Table 3, entries 4–7) which were either sluggish or ineffective. Among the copper(I) sources examined, CuCl gave the highest enantioselectivity of 79% ee and was therefore used for further optimization (Table 3, entry 1).

Subsequently, the effects of ratio of ligand (*R*)-**1a** to CuCl, catalyst loading and reaction temperature were examined. When the amount of CuCl was kept constant at 10 mol %, a gradual increase in the amount of ligand (*R*)-**1a** from 5, 10, 15 to 20 mol % (Table 4 entries 1–4) resulted in a tremendous increase in the reaction rate and the yield of **3a** more than doubled when the amount of ligand

Table 2
Screening of solvents in the enantioselective Henry reaction[a]

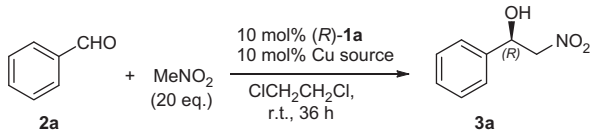


2a 3a

Entry	Solvent	Yield[b] (%)	ee[c] (%)
1	Methanol	84	30
2	Ethanol	89	26
3	CH_2Cl_2	78	57
4	$ClCH_2CH_2Cl$	45	77
5	$CHCl_3$	56	34
6	Toluene	91	29
7	CH_3CN	89	55
8	THF	94	68
9	Dioxane	99	42
10	1,2-Dimethoxyethane	38	70
11	*t*-BuOMe	90	62
12	Bu_2O	99	64
13	Et_2O	35	58

[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde **2a** in the presence of ligand (10 mol %) and CuBr (10 mol %) using $MeNO_2$ (20 equiv) in a given solvent (1.5 ml) at rt for 36 h.
[b] Yield of isolated product.
[c] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H column. The absolute configuration (*R*) was determined by comparison with the literature values.[8d]

Table 3
Screening of copper sources in the enantioselective Henry reaction[a]



2a 3a

Entry	Copper	Yield[b] (%)	ee[c] (%)
1	CuCl	55	79
2	CuBr	45	77
3	CuI	70	41
4	$CuCl_2$	0	—
5	$Cu(OAc)_2$	21	68
6	$Cu(NO_3)_2$	0	—
7	$Cu(OTf)_2$	0	—

[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde in the presence of ligand (10 mol %) and copper sources (10 mol %) using $MeNO_2$ (20 equiv) in $ClCH_2CH_2Cl$ (1.5 ml) at rt for 36 h.
[b] Yields of isolated products.
[c] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H column. The absolute configuration (*R*) was determined by comparison with the literature values.[8d]

(*R*)-**1a** was increased from 5 to 10 mol % (Table 4, entries 2 vs 1). However, the yield of **3a** remained unchanged with a further increase in the amount of (*R*)-**1a** (Table 4, entry 2 vs entries 3 and 4). A slight increase in the ee of compound **3a** was also observed (Table 4 entries 1–4). However, a gradual increase in the amount of CuCl from 5, 15 to 20 mol %, while keeping the amount of ligand (*R*)-**1a** constant at 10 mol %, led to a significant decrease in the yield of **3a** from 63% to 19% to 13%, respectively, accompanied by a slight decrease in enantioselectivity from 83% to 74% to 71%, respectively, (Table 4, entries 5–7). Based on the above results, we concluded that the optimal ratio of ligand (*R*)-**1a** to CuCl is 2:1 (Table 4, entry 5). Attempts to half the catalyst loading while maintaining the (*R*)-**1a** to CuCl ratio at 2:1, resulted in a much lower yield of **3a** (16%) even at extended reaction time (Table 4, entry 8). Therefore, the optimal ratio between (*R*)-**1a** and CuCl is 2:1 using 10 mol % ligand (*R*)-**1a** and 5 mol % CuCl loading.

The effect of reaction temperature was examined at 40 °C, 0 °C and −20 °C. An increase in the reaction temperature from rt to 40 °C resulted in a faster reaction rate, improved yield of **3a** (78%) but inferior enantioselectivity (70% ee) (Table 4, entry 9 vs entry 5). However, a decrease in the reaction temperature from rt to 0 °C gave comparable yield (60%) and higher enantioselectivity (85% ee) of **3a** (Table 4, entry 10 vs entry 5). At −20 °C, the reaction did not proceed due to poor solubility of the copper complex (Table 4, entry 11).

Since the most effective ratio of (*R*)-**1a** to CuCl was 2:1 (Table 4, entry 10), the solvent and copper sources effects were reexamined in the hope of obtaining better yields and enantioselectivities (Table 5). Again, the best results obtained in this case are in agreement with the solvent and copper sources effects shown in Table 2 and Table 3, respectively. Dichloroethane (Table 5, entry 1 vs entries 2–6) using Cu(I) sources (Table 5, entries 1 and 7 vs entry 8) gave the best results.

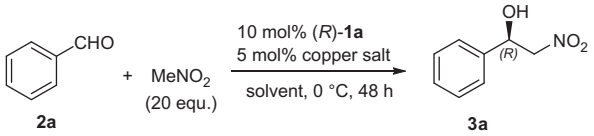
The scope and limitation of the Henry reaction using ligand (*R*)-**1a** under the optimized conditions (Table 4, entry 10) were examined. We were delighted to find that a broad range of aliphatic and aromatic aldehydes reacted smoothly with $MeNO_2$ using our catalytic system to give the corresponding β-nitroalcohols in high yields and enantioselectivities (Table 6). Aromatic aldehydes with electron-withdrawing (Table 6, entries 2–6) and electron-donating substituents (Table 6, entries 7–13) gave similar yields (up to 95%) and enantioselectivities (up to 91% ee). An exception to this is 4-nitrobenzaldehyde, which due to its strong electron-withdrawing nitro group; it exerted a much faster reaction rate that led to higher yield (95%) and lower enantioselectivity (64% ee). Interestingly, the substitution pattern (Table 6, entries 3–5, 7–9 and 11–13) at the aromatic rings exhibited no major effect on the enantioselectivity or yield of the products. In general, aliphatic and α,β-conjugated aldehydes give lower enantioselectivities compared to aromatic aldehydes due to the higher inherent reactivity and poor stereocontrol as a result of substrate flexibility. We were pleased to discover that the (*R*)-**1a**–Cu(I) complex catalyzed the nitroaldol reaction of aliphatic and α,β-conjugated aldehydes to give the corresponding β-nitroalcohol **3p**–**3s** in up 91% ee (Table 6, entries 16–18). 2-Naphthylaldehyde, 2-furaldehyde and cinamaldehyde gave the corresponding products in very good yields and enantioselectivities (Table 6, entries 14, 15 and 19).

It is essential that new catalysts designed for the Henry reaction should circumvent side reactions such as the formation of a nitroalkene, normal aldol by-products and epimerization of stereogenic centers remote from the nitro group. Fortunately, with the present catalytic system, no such products were observed and no special precautions were taken to exclude moisture or air from the reaction flask.

The nonlinear effects were also examined (Fig. 3). The data shown in Table 7 for the Henry reaction between benzaldehyde **2a** and nitromethane seems to fit well with Kagan's ML_4 model system, which could mean the involvement of an aggregation of dimers.[18] Assuming the ligands are statistically distributed between the complexes, curve fitting was calculated from the following equation[18c] with parameters $ee_o = 85\%$ (enantioselectivity of the reaction performed with enantiopure ligand), $K = [M(L_R)_3L_S]^2/\{[M(L_R)_4] * [M(L_R)_2(L_S)_2]\} = [M(L_S)_3L_R]^2/\{[M(L_S)_4] * [M(L_R)_2(L_S)_2]\} = 1000$, $ee'_o = 64\%$, $g = 0.41$ (large predominance of a fairly active and selective heterochiral catalyst), and $K' = [M(L_R)_2(L_S)_2]^2/\{[M(L_R)_3L_S] * [M(L_S)_3L_R]\} = 1$, $f = 2.0$ (a more active meso catalyst).

$$ee_{prod} = 8ee_o * ee_{cat} \times \frac{1 + ee_{cat}^2 + 2g(1 - ee_{cat}^2)\frac{ee'_o}{ee_o}}{(1 + ee_{cat})^4 + (1 - ee_{cat})4 + 8g(1 - ee_{cat})4 + 6f(1 - ee_{cat}^2)^2}$$

Table 4
Effects of the ratio of (*R*)-**1a** to CuCl, catalyst loading and temperature in the asymmetric Henry reaction of benzaldehyde[a]

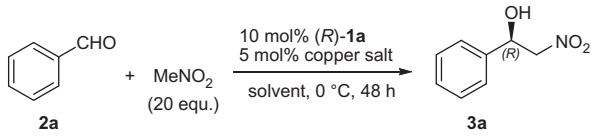


2a **3a**

Entry	CuCl (mol%)	(*R*)-**1a** (mol%)	Temperature (°C)	Time (h)	Yield[b] (%)	ee[c] (%)
1	10	5	rt	84	25	73
2	10	10	rt	36	55	79
3	10	15	rt	36	56	80
4	10	20	rt	36	56	82
5	5	10	rt	36	63	83
6	15	10	rt	36	19	74
7	20	10	rt	36	13	71
8	2.5	5	rt	120	16	80
9	5	10	40	12	78	70
10	5	10	0	72	60	85
11	5	10	−20	120	—	—

[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde in the presence of ligand (*R*)-**1a** and CuCl using $MeNO_2$ (20 equiv) in $ClCH_2CH_2Cl$ (1.5 ml).
[b] Yield of isolated product.
[c] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H column. The absolute configuration (*R*) was determined by comparison with the literature values.[8d]

Table 5
Screening of solvents and copper sources using a 2:1 ratio of (*R*)-**1a**–copper source in the enantioselective Henry reaction[a]

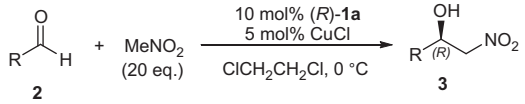


2a **3a**

Entry	Solvent	Copper	Yield[b] (%)	ee[c] (%)
1[d]	$ClCH_2CH_2Cl$	CuCl	60	85
2	Methanol	CuCl	90	36
3	CH_2Cl_2	CuCl	78	70
4	Toluene	CuCl	70	65
5	CH_3CN	CuCl	85	70
6	THF	CuCl	90	66
7[d]	$ClCH_2CH_2Cl$	CuBr	55	78
8[d]	$ClCH_2CH_2Cl$	$Cu(OAc)_2$	40	62

[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde in the presence of ligand (*R*)-**1a** (10 mol %) and Copper salts (5 mol %) using $MeNO_2$ (20 equiv) in $ClCH_2CH_2Cl$ (1.5 ml).
[b] Yield of isolated product.
[c] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H column. The absolute configuration (*R*) was determined by comparison with the literature values.[8d]
[d] Reaction for 72 h.

Table 6
Scope of (*R*)-**1a** in the enantioselective Henry reaction[a]



2 **3**

Entry	R	Product	Time (h)	Yield[b] (%)	ee[c] (%)
1	Ph	**3a**	72	60	85
2	$4\text{-}NO_2C_6H_4$	**3b**	12	95	64
3	$4\text{-}ClC_6H_4$	**3c**	48	70	91
4	$3\text{-}ClC_6H_4$	**3d**	60	59	87
5	$2\text{-}ClC_6H_4$	**3e**	48	72	87
6	$4\text{-}FC_6H_4$	**3f**	72	59	87
7	$4\text{-}MeC_6H_4$	**3g**	60	65	88
8	$3\text{-}MeC_6H_4$	**3h**	60	57	86
9	$2\text{-}MeC_6H_4$	**3i**	48	70	87
10	$4\text{-}PhC_6H_4$	**3j**	48	80	82
11	$4\text{-}MeOC_6H_4$	**3k**	72	60	89
12	$3\text{-}MeOC_6H_4$	**3l**	48	75	90
13	$2\text{-}MeOC_6H_4$	**3m**	48	79	91
14	2-Naphthyl	**3n**	48	85	80
15	2-Fural	**3o**	48	80	85
16	*n*-Bu	**3p**	60	76	88
17	*n*-Pr	**3q**	60	73	90
18	$n\text{-}C_8H_{17}$	**3r**	48	72	91
19	PhCH=CH–	**3s**	48	78	81

[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde in the presence of ligand (*R*)-**1a** (10 mol %) and CuCl (5 mol %) using $MeNO_2$ (20 equiv) in $ClCH_2CH_2Cl$ (1.5 ml) at 0 °C.
[b] Yield of isolated product.
[c] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H, OJ-H or AD-H column. The absolute (*R*) configuration was determined by comparison with the literature values.[5a,8d]

where $g = k_{RRRS}/k_{RRRR}$, relative reactivities of hetero ($M(L_R)_3L_S$) over homochiral catalysts, $f = k_{RRSS}/k_{RRRR}$, relative reactivities of hetero-meso kind ($M(L_R)_2(L_S)_2$) over homochiral catalysts, ee_{prod} = ee of the Henry reaction's product obtained, ee_o = ee of the Henry reaction's product obtained using enantiopure homochiral $M(L_R)_4$ complexes, ee'_o = ee of the obtained Henry reaction's product using enantiopure heterochiral $M(L_R)_3L_S$ complexes (we consider $M(L_R)_2(L_S)_2$ as a meso complex and assume no additional stereoisomers involving the metal center),[18c] ee_{cat} = ee of ligand.

3. Conclusion

We have shown that the reactivities and selectivities of chiral C_1-tetrahydro-1,1′-bisisoquinolines in the Henry reaction are governed to a great extent by the type of substituent at the sp^3-*N*. Chiral C_1-tetrahydro-1,1′-bisisoquinoline (*R*)-**1a** proved to be an effective ligand in the Cu(I)-catalyzed Henry reaction. The desired products were obtained in excellent yields and enantioselectivities (up to 91%) with a broad range of aliphatic, aromatic, heteroaromatic and unsaturated aldehydes. The nonlinear effects fit well with the Kagan's ML_4 model system. The operational procedure using the present catalyst system is very simple and does not require exclusion of air or moisture. The results obtained here pave the way for more applications of

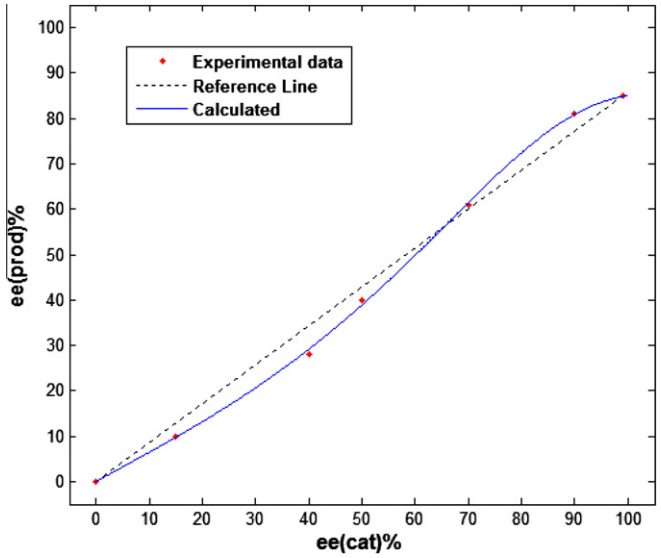
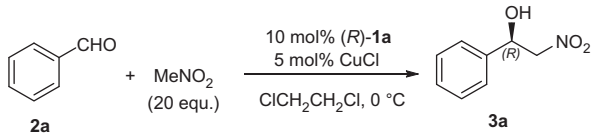


Figure 3. Nonlinear effect for the Henry reaction of nitromethane and benzaldehyde catalyzed by the (*R*)-**1a**/CuCl (2/1) system.

Table 7
Nonliear effect under 2:1 ratio of (*R*)-**1a**–Copper salt in the enantioselective Henry reaction[a]



Entry	% ee Catalyst, (*R*)-**1a**	% ee Product, **3a** [b]
1	0	0
2	15	10
3	40	28
4	50	40
5	70	61
6	90	81
7	99	85

[a] All reactions were performed on a 0.2 mmol scale of benzaldehyde in the presence of ligand (*R*)-**1a** (10 mol %) and CuCl (5 mol %) using $MeNO_2$ (20 equiv) in $ClCH_2CH_2Cl$ (1.5 ml).

[b] Enantiomeric excesses were determined by HPLC using a Chiralcel OD-H column. The absolute configuration (*R*) was determined by comparison with the literature values.[8d]

the C_1-tetrahydro-1,1′-bisisoquinoline ligands in various asymmetric reactions.

4. Experimental

4.1. General

All commercial chemicals were reagent grade unless otherwise specified. Analytical thin layer chromatography (TLC) was performed using Merck 60 F_{254} pre-coated silica gel plates (0.2 mm thickness). Separation of products was achieved using column chromatography on Merck Silica Gel 60 (230–400 mesh). ^1H (300 MHz) and ^{13}C (75.47 MHz) NMR spectra were recorded on a Bruker Advanced DPX 300 spectrometer with TMS as an internal reference. HPLC separations were performed on Agilent 1100 using Diacel Chiralcel OD-H, OJ-H and AD-H chiral columns.

4.2. General procedure for asymmetric Henry reaction

Ligand (0.02 mmol, 10 mol %) and CuCl (0.01 mmol, 5 mol %) were stirred in $ClCH_2CH_2Cl$ (1.5 mL) at rt for 100 min, whereby a green solution was obtained. To the above stirred solution, aldehyde (0.2 mmol) was added and the mixture was stirred for another 5 min before the dropwise addition of nitromethane (4 mmol, 20 equiv). The reaction mixture was further stirred at the given temperature for a specific time (TLC). The β-nitroalcohol product was purified on silica gel by flash column chromatography.

4.2.1. (*R*)-1-Phenyl-2-nitroethanol (*R*)-3a

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a colorless oil (60% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 0.8 ml/min, 215 nm); major enantiomer t_1 = 18.10 min, minor enantiomer t_2 = 22.20 min; 85% ee; ^1H NMR ($CDCl_3$, δ ppm): 2.76 (1H, br s), 4.39–4.56 (2H, m), 5.37 (1H, dd, J = 9.3, 9.6 Hz), 7.34–7.40 (5H, m); ^{13}C NMR: 71.0, 81.3, 126.0, 129.0, 129.1 and 138.2.

4.2.2. (*R*)-1-(4-Nitrophenyl)-2-nitroethanol (*R*)-3b

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 7:3) to give a yellow oil (95% yield); HPLC analysis: Chiralcel OD-H column (85:15 *n*-hex: IPA, flow rate 1.0 ml/min, 215 nm); major enantiomer t_1 = 21.10 min, minor enantiomer t_2 = 25.50 min; 64% ee; ^1H NMR ($CDCl_3$, δ ppm): 3.28 (1H, br s), 4.47–4.66 (2H, m), 5.48–5.5.56 (1H, m), 7.63 (2H, d, J = 8.7 Hz), 8.27 (2H, d, J = 8.7 Hz); ^{13}C NMR ($CDCl_3$, δ ppm): 70.0, 80.6, 124.1, 127.0, 145.4 and 148.0.

4.2.3. (*R*)-1-(4-Chlorophenyl)-2-nitroethanol (*R*)-3c

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a colorless oil (70% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 1.0 ml/min, 215 nm); major enantiomer t_1 = 13.90 min, minor enantiomer t_2 = 17.70 min; 91% ee; ^1H NMR ($CDCl_3$, δ ppm): 2.89 (1H, br s), 4.47–4.62 (2H, m), 5.44–5.47 (1H, m), 7.34–7.40 (4H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 70.3, 80.1, 127.3, 129.3, 134.9 and 136.5.

4.2.4. (*R*)-1-(3-Chlorophenyl)-2-nitroethanol (*R*)-3d

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a colorless oil (59% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 1.0 ml/min, 215 nm); major enantiomer t_r = 13.6 min, minor enantiomer t_r = 16.8 min; 87% ee; ^1H NMR ($CDCl_3$, δ ppm): 2.96 (1H, br s), 4.49–4.63 (2H, m), 5.40 (1H, m), 7.26–7.73 (4H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 70.3, 81.0, 124.0, 126.2, 129.1, 130.3, 135.0 and 140.0.

4.2.5. (*R*)-1-(2-Chlorophenyl)-2-nitroethanol (*R*)-3e

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a colorless oil (72% yield); HPLC analysis: Chiralcel OJ-H column (90:10 *n*-hex: IPA, flow rate 0.5 ml/min, 215 nm); major enantiomer t_1 = 82.00 min, minor enantiomer t_2 = 94.37 min; 87% ee; ^1H NMR ($CDCl_3$, δ ppm): 3.00 (1H, br s), 4.59–4.64 (1H, m), 4.62 (1H, dd, J = 13.5, 2.4 Hz), 5.79 (1H, d, J = 9.3 Hz), 7.26–7.34 (3H, m), 7.60 (1H, dd, J = 9.3, 2.1 Hz); ^{13}C NMR ($CDCl_3$, δ ppm): 67.8, 79.3, 127.5, 127.6, 129.7, 129.9, 131.5 and 135.5.

4.2.6. (*R*)-1-(4-Fluorophenyl)-2-nitroethanol (*R*)-3f

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 7:3) to give a colorless oil (59% yield); HPLC analysis: Chiralcel OD-H column

(90:10 *n*-hex: IPA, flow rate 0.8 ml/min, 215 nm); major enantiomer t_1 = 15.37 min, minor enantiomer t_2 = 18.36 min; 87% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.89 (1H, s), 4.46–4.63 (2H, m), 5.47 (1H, d, J = 7.5 Hz), 7.07–7.13 (2H, m), 7.37–7.42 (2H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 70.3, 81.2, 115.9, 116.1, 127.7 and 127.8.

4.2.7. (*R*)-1-(4-Methylphenyl)-2-nitroethanol (*R*)-3g

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 8:1) to give a colorless oil (65% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 0.5 ml/min, 215 nm); major enantiomer t_1 = 27.8 min, minor enantiomer t_2 = 35.6 min; 88% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.36 (3H, s), 2.48 (1H, s), 4.46–4.64 (2H, m), 5.40–5.46 (1H, m), 7.26–7.30 (4H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 21.2, 70.9, 81.3, 125.9, 129.7, 135.2 and 139.0.

4.2.8. (*R*)-1-(3-Methylphenyl)-2-nitroethanol (*R*)-3h

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (57% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 0.5 ml/min, 215 nm); major enantiomer t_1 = 23.9 min, minor enantiomer t_2 = 27.9 min; 86% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.38 (3H, s), 2.81 (1H, s), 4.50–4.65 (2H, m), 5.37–5.45 (1H, m), 7.23–7.32 (4H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 21.4, 71.1, 81.8, 123.0, 126.6, 128.9, 129.7, 138.0 and 138.9.

4.2.9. (*R*)-1-(2-Methylphenyl)-2-nitroethanol (*R*)-3i

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a colorless oil (70% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 0.5 ml/min, 215 nm); major enantiomer t_1 = 23.29 min, minor enantiomer t_2 = 36.60 min; 87% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.40 (3H, s), 2.72 (1H, d, J = 3.6 Hz), 4.42–4.60 (2H, m), 5.67–5.72 (1H, m), 7.25–7.31 (3H, m), 7.51–7.56 (1H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 18.9, 68.0, 80.2, 125.6, 126.8, 128.8, 130.9, 134.4 and 136.2.

4.2.10. (*R*)-1-(4-Phenylphenyl)-2-nitroethanol (*R*)-3j

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a pale yellow crystalline solid (80% yield); HPLC analysis: Chiralcel OD-H column (85:15 *n*-hex: IPA, flow rate 0.8 ml/min, 215 nm); major enantiomer t_1 = 19.54 min, minor enantiomer t_2 = 23.80 min; 82% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.88 (1H, d, J = 3.3 Hz), 4.36–4.69 (2H, m), 5.52 (1H, d, J = 9.3 Hz), 7.34–7.64 (9H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 70.8, 81.2, 126.4, 127.1, 127.7, 127.8, 128.9, 137.0, 140.3 and 142.0.

4.2.11. (*R*)-1-(4-Methoxyphenyl)-2-nitroethanol (*R*)-3k

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (60% yield); HPLC analysis: Chiralcel OD-H column (85:15 *n*-hex: IPA, flow rate 0.8 ml/min, 215 nm); major enantiomer t_1 = 17.01 min, minor enantiomer t_2 = 21.78 min; 89% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.73 (1H, br s), 3.81 (3H, s), 4.45–4.66 (2H, m), 5.62–5.68 (1H, m), 6.93 (2H, d, J = 8.7 Hz), 7.26–7.34 (2H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 55.4, 70.7, 81.3, 114.4, 127.3, 130.2 and 160.1.

4.2.12. (*R*)-1-(3-Methoxyphenyl)-2-nitroethanol (*R*)-3l

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 4:1) to give a yellow oil (75% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 0.5 ml/min, 215 nm); major enantiomer t_1 = 48.22 min, minor enantiomer t_2 = 63.57 min; 90% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.97 (1H, br s), 3.19 (3H, s), 4.72–4.84 (2H, m), 5.44 (1H, m), 6.88–6.97 (3H, m), 7.28–7.57 (1H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 55.3, 70.9, 81.2, 111.50, 114.4, 118.1, 130.1, 139.8 and 160.1.

4.2.13. (*R*)-1-(2-Methoxyphenyl)-2-nitroethanol (*R*)-3m

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 9:1) to give a yellow oil (79% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 1.0 ml/min, 215 nm); major enantiomer t_1 = 11.14 min, minor enantiomer t_2 = 12.91 min; 91% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 3.24 (1H, d, J = 6 Hz), 3.90 (3H, s), 4.55–4.69 (2H, m), 5.62–5.68 (1H, m), 6.93 (1H, d, J = 8 Hz), 7.03 (1H, t, J = 7.5 Hz), 7.35 (1H, t, J = 8 Hz), 7.46 (1H, d, J = 7.5 Hz); ^{13}C NMR ($CDCl_3$, δ ppm): 55.4, 67.8, 79.9, 110.6, 121.2, 126.0, 127.2, 129.8 and 156.0.

4.2.14. (*R*)-1-(2-Naphthyl)-2-nitroethanol (*R*)-3n

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 4:1) to give a yellow solid (85% yield); HPLC analysis: Chiralcel OD-H column (85:15 *n*-hex: IPA, flow rate 0.8 ml/min, 215 nm); major enantiomer t_1 = 36.13 min, minor enantiomer t_2 = 51.62 min; 80% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 3.04 (1H, br s), 4.54–4.82 (2H, m), 5.61 (1H, d, J = 6.9 Hz), 7.26–7.54 (3H, m), 7.84–7.88 (4H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 71.2, 81.2, 123.2, 125.3, 126.7, 126.7, 127.8, 128.1, 129.0, 133.2, 133.4 and 135.4.

4.2.15. (*R*)-1-(2-Fural)-2-nitroethanol (*R*)-3o

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (80% yield); HPLC analysis: Chiralcel OJ-H column (90:10 *n*-hex: IPA, flow rate 1.0 ml/min, 215 nm); major enantiomer t_1 = 23.08 min, minor enantiomer t_2 = 28.49 min; 85% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.90 (1H, br s), 4.63–4.84 (2H, m), 5.40–5.50 (1H, m), 6.38–6.40 (2H, m), 7.40–7.42 (1H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 64.9, 78.4, 108.2, 100.7, 143.2 and 150.7.

4.2.16. (*R*)-1-Nitrohexan-2-ol (*R*)-3p

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (76% yield); HPLC analysis: Chiralcel AD-H column (98:2 *n*-hex: IPA, flow 0.8 ml/min, 215 nm); major enantiomer t_1 = 37.80 min, minor enantiomer t_2 = 50.51 min; 88% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 0.94 (3H, t, J = 6.9 Hz), 1.34–1.61 (6H, m), 2.54 (1H, br s), 4.31–4.49 (3H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 13.9, 22.4, 27.3, 33.4, 68.7 and 80.6.

4.2.17. (*R*)-1-Nitropentan-2-ol (*R*)-3q

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (73% yield); HPLC analysis: Chiralcel AD-H column (98:2 *n*-hex: IPA, flow 1.0 ml/min, 215 nm); major enantiomer t_1 = 33.70 min, minor enantiomer t_2 = 57.18 min; 90% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 0.98 (3H, t, J = 6.9 Hz), 1.50–1.59 (4H, m), 2.53 (1H, br s), 4.35–4.46 (3H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 13.7, 18.4, 35.8, 68.4 and 80.7.

4.2.18. (*R*)-1-Nitrodecan-2-ol (*R*)-3r

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (72% yield); HPLC analysis: Chiralcel AD-H column (98:2 *n*-hex: IPA, flow rate 1.0 ml/min, 215 nm); major enantiomer t_1 = 23.09 min, minor enantiomer t_2 = 36.73 min; 91% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 0.88 (3H, t, J = 6.3), 1.47–1.50 (14H, m), 2.49 (1H, d, J = 4.5 Hz), 4.34–4.47 (3H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 14.1, 22.6, 25.2, 29.2, 29.3, 29.4, 31.8, 33.7, 68.7 and 80.6.

4.2.19. (*R*,*E*)-1-Nitro-4-phenyl-3-buten-2-ol (*R*,*E*)-3s

This compound was prepared according to the Section 4.2 and purified by column chromatography (Hexane–EtOAc 5:1) to give a yellow oil (78% yield); HPLC analysis: Chiralcel OD-H column (90:10 *n*-hex: IPA, flow rate 0.8 ml/min, 215 nm); minor enantiomer t_r = 38.62 min, major enantiomer t_r = 42.77 min; 81% ee; ^{1}H NMR ($CDCl_3$, δ ppm): 2.68 (1H, d, J = 3.9 Hz), 4.51–4.61 (2H, m), 5.06 (1H, br s), 6.15 (1H, dd, J = 6.3, 15.9 Hz), 6.79 (1H, d, J = 15 Hz), 7.30–7.46 (5H, m); ^{13}C NMR ($CDCl_3$, δ ppm): 69.6, 79.9, 124.9, 126.7, 128.6, 128.8, 133.7 and 135.5.

Acknowledgments

We are grateful to the Nanyang Technological University for financial support (RG27/07), and also appreciate scholarship support for Y. Qiong Ji from China Scholarship Council.

References

1. (a) Cavell, K. J.; Elliott, M. C.; Nielsen, D. J.; Paine, J. S. *Dalton Trans.* **2006**, 4922–4925; (b) Arai, S.; Takita, S.; Nishida, A. *Eur. J. Org. Chem.* **2005**, *24*, 5262–5267; (c) Seo, H.; Hirsch-Weil, D. K.; Abboud, A.; Hong, S. *J. Org. Chem.* **2008**, *73*, 1983–1986; (d) Baskakov, D.; Herrmann, W. A.; Herdtweck, E.; Hoffmann, S. D. *Organometallics* **2007**, *26*, 626–632; (e) Herrmann, W. A.; Baskakov, D.; Herdtweck, E.; Hoffmann, S. D.; Bunlaksananusorn, T.; Rampf, F.; Rodefeld, L. *Organometallics* **2006**, *25*, 2449–2456; (f) Hrdina, R.; Dra ccaron ínský, M.; Valterová, I.; Hoda ová, J.; Císa rcaron, I.; Kotora, M. *Adv. Synth. Catal.* **2008**, *350*, 1449–1456; Yao, Q.-J.; Judeh, Z. M. A. *Tetrahedron* **2011**, *67*, 4086–4092.
2. (a) Qi, G.; Yao, Q.-J.; Judeh, Z. M. A. *Tetrahedron* **2010**, *66*, 4195–4205; (b) Qi, G.; Judeh, Z. M. A. *Tetrahedron: Asymmetry* **2010**, *21*, 429–436; (c) Busato, S.; Craig, D. C.; Judeh, Z. M. A.; Read, R. W. *Tetrahedron* **2003**, *59*, 461–472; (d) Craig, D. C.; Judeh, Z. M. A.; Read, R. W. *Aust. J. Chem.* **2002**, *55*, 733–736; (e) Judeh, Z. M. A.; Ching, C. B.; McCluskey, A.; Bu, J. *Tetrahedron Lett.* **2002**, *43*, 5089–5091; (f) Shen, H.-Y.; Ying, L.-Y.; Jiang, H.-L.; Judeh, Z. M. A. *Int. J. Mol. Sci.* **2007**, *8*, 505–512.
3. (a) Ono, N. *The Nitro Group in Organic Synthesis*; Wiley-VCH: New York, 2001; (b) Rosini, G. In *Comprehensive Organic synthesis*; Pergamon: New York, 1991; Vol. 2, (c) Poupart, M.-A.; Fazal, G.; Goulet, S.; Mar, L. T. *J. Org. Chem.* **1999**, *64*, 1356–1361; (d) Matt, C.; Wagner, A.; Mioskowski, C. *J. Org. Chem.* **1997**, *62*, 234–235; (e) Palomo, C.; Oiarbide, M.; Laso, A. *Eur. J. Org. Chem.* **2007**, *16*, 2561–2574; (f) Boruwa, J.; Gogoi, N.; Saikia, P. P.; Barua, N. C. *Tetrahedron: Asymmetry* **2006**, *17*, 3315–3326; (g) Mayani, V. J.; Abdi, S. H. R.; Kureshy, R. I.; Khan, N. H.; Das, A.; Bajaj, H. C. *J. Org. Chem.* **2010**, *75*, 6191–6195.
4. Sasai, H.; Suzuki, T.; Arai, S.; Arai, T.; Shibasaki, M. *J. Am. Chem. Soc.* **1992**, *114*, 4418–4420.
5. (a) Evans, D. A.; Seidel, D.; Rueping, M.; Lam, H. W.; Shaw, J. T.; Downey, C. W. *J. Am. Chem. Soc.* **2003**, *125*, 12692–12693; (b) Christensen, C.; Juhl, K.; Hazell, R. G.; Jorgensen, K. A. *J. Org. Chem.* **2002**, *67*, 4875–4881; (c) Risgaard, T.; Gothelf, K. V.; Jorgensen, K. A. *Org. Biomol. Chem.* **2003**, *1*, 153–156; (d) Du, D.-M.; Lu, S.-F.; Fang, T.; Xu, J. *J. Org. Chem.* **2005**, *70*, 3712–3715; (e) Lang, K.; Park, J.; Hong, S. *J. Org. Chem.* **2010**, *75*, 6424–6435.
6. Ma, K.; You, J. *Chem. Eur. J.* **2007**, *13*, 1863–1871.
7. Maheswaran, H.; Prasanth, K. L.; Krishna, G. G.; Ravikumar, K.; Sridhar, B.; Kantam, M. L. *Chem. Commun.* **2006**, 4066–4068.
8. (a) Arai, T.; Takashita, R.; Endo, Y.; Watanabe, M.; Yanagisawa, A. *J. Org. Chem.* **2008**, *73*, 4903–4906; (b) Arai, T.; Watanabe, M.; Yanagisawa, A. *Org. Lett.* **2007**, *9*, 3595–3597; (c) Bandini, M.; Benaglia, M.; Sinisi, R.; Tommasi, S.; Umani-Ronchi, A. *Org. Lett.* **2007**, *9*, 2151–2153; (d) Bandini, M.; Piccinelli, F.; Tommasi, S.; Umani-Ronchi, A.; Ventrici, C. *Chem. Commun.* **2007**, 616–618.
9. (a) Blay, G.; Climent, E.; Fernández, I.; Hernández-Olmos, V.; Pedro, J. R. *Tetrahedron: Asymmetry* **2006**, *17*, 2046–2049; (b) Blay, G.; Domingo, L. R.; Hernández-Olmos, V.; Pedro, J. R. *Chem. Eur. J.* **2008**, *14*, 4725–4730; (c) Noole, A.; Lippur, K.; Metsala, A.; Lopp, M.; Kanger, T. *J. Org. Chem.* **2010**, *75*, 1313–1316.
10. Xiong, Y.; Wang, F.; Huang, X.; Wen, Y.; Feng, X. *Chem. Eur. J.* **2007**, *13*, 829–833.
11. Qin, B.; Xiao, X.; Liu, X.; Huang, J.; Wen, Y.; Feng, X. *J. Org. Chem.* **2007**, *72*, 9323–9328.
12. Sohtome, Y.; Hashimoto, Y.; Nagasawa, K. *Adv. Synth. Catal.* **2005**, *347*, 1643–1648.
13. Kogami, Y.; Nakajima, T.; Ikeno, T.; Yamada, T. *Synthesis* **2004**, *12*, 1947–1950.
14. (a) Palomo, C.; Oiarbide, M.; Laso, A. *Angew. Chem., Int. Ed.* **2005**, *44*, 3881–3884; (b) Trost, B. M.; Yeh, V. S. C. *Angew. Chem., Int. Ed.* **2002**, *41*, 861–863; (c) Trost, B. M.; Yeh, V. S. C.; Ito, H.; Bremeyer, N. *Org. Lett.* **2002**, *4*, 2621–2623.
15. Kowalczyk, R.; Kwiatkowski, P.; Skarżewski, J.; Jurczak, J. *J. Org. Chem.* **2008**, *74*, 753–756.
16. (a) Arai, T.; Yamada, Y. M. A.; Yamamoto, N.; Sasai, H.; Shibasaki, M. *Chem. Eur. J.* **1996**, *2*, 1368–1372; (b) Sasai, H.; Tokunaga, T.; Watanabe, S.; Suzuki, T.; Itoh, N.; Shibasaki, M. *J. Org. Chem.* **1995**, *60*, 7388–7389.
17. Xi, H.-W.; Judeh, Z. M. A.; Lim, K. H. *J. Mol. Struct.* **2009**, *897*, 22–31.
18. (a) Girard, C.; Kagan, H. B. *Angew. Chem., Int. Ed.* **1998**, *37*, 2922–2959; (b) Satyanarayana, T.; Abraham, S.; Kagan, H. B. *Angew. Chem., Int. Ed.* **2009**, *48*, 456–494; (c) Guillaneux, D.; Zhao, S. H.; Samuel, O.; Rainford, D.; Kagan, H. B. *J. Am. Chem. Soc.* **1994**, *116*, 9430–9439.