Tetrahedron 67 (2011) 8445–8450

Contents lists available at SciVerse ScienceDirect

Tetrahedron

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

Iridium-catalyzed asymmetric hydrogenation of 3-substituted unsaturated oxindoles to prepare C3-mono substituted oxindoles

Yuanyuan Liu, Dongmei Yao, Kun Li, Fengtao Tian, Fang Xie, Wanbin Zhang *

School of Chemistry and Chemical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 26 July 2011
Received in revised form 3 September 2011
Accepted 9 September 2011
Available online 12 September 2011

Keywords:
Asymmetric hydrogenation
Iridium complex
Tropos phosphine–oxazoline ligands
3-Substituted unsaturated oxindoles
Chiral C3-mono substituted oxindoles

ABSTRACT

An efficient and enantioselective hydrogenation of 3-substituted unsaturated oxindoles has been developed by an iridium complex of *tropos* phosphine–oxazoline ligands. It is the first example to prepare chiral C3-mono substituted oxindoles via asymmetric catalysis. And the reaction provides instant access to this kind of compounds with excellent conversion and enantioselectivities (up to 93% ee).

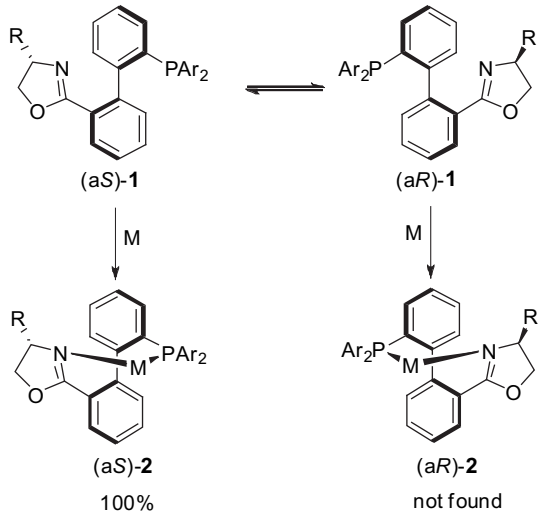
1. Introduction

Owing to its abundance in natural products and pharmaceutically active compounds,[1] the 3-substituted oxindole framework has attracted special synthetic attention,[2] and much effort has already been dedicated to the catalytic asymmetric construction of chiral C3-quaternary centers in the oxindole framework.[3,4] Good to excellent yields and enantioselectivities were obtained by employing in a variety of substrates. Although most of the natural oxindole products possess chiral C3-quaternary centers, the chiral C3-mono substituted oxindole is also an important framework for some natural products and drug candidates.[5] One example is the welwitindolinone, a family of unusual oxindole alkaloids isolated from the cyanobacteria *Hapalosiphon welwischii* and *Westiella intricate*, which is responsible for the multiple drug resistance (MDR) reversing activity of the algal extracts, elucidated by Moore and co-workers in 1994.[5e] However, the synthesis of chiral C3-mono substituted oxindole framework is rarely reported. The only example was achieved via transfer of axial chirality in radical cyclizations by Curran and co-workers in 1999.[6] In their work, 60–93% yields and 49–92% enantioselectivities were obtained using stoichiometric enantiopure substrates. Thus, it is essential to develop straightforward and catalytic approaches to chiral C3-mono substituted oxindoles in order to meet demand of organic synthesis and drug research. The metal-catalyzed asymmetric hydrogenation of 3-substituted unsaturated oxindoles would be one of the best choices. However, to the best of our knowledge, no efforts have been focused on this topic.

Asymmetric hydrogenation by means of efficient chiral catalyst is one of the most important catalytic methods for the preparation of optically active compounds. In numerous catalyst systems, iridium complexes with chiral P,N-ligands have attracted much attention because of their easy availability, high reactivity and enantioselectivity.[7] In the past decades, chiral phosphine–oxazoline ligands with an axis-fixed binaphthyl backbone were developed by us and other groups and showed excellent chirality transfer properties in asymmetric catalysis.[8] However, in most cases, only one of the two diastereomers of the ligands works effectively due to the configurationally matching-mismatching effect. Bearing this in mind, recent years we designed a novel kind of *tropos* chiral phosphine–oxazoline ligands **1**, which exist as an equilibrium mixture of diastereomers in solution as a result of rotation around the internal bond of the biphenyl (Scheme 1). When these ligands coordinated to Pd(II) or Ir(I), interestingly, only one of the two possible diastereomeric complexes **2** was formed and showed excellent catalytic activity and enantioselectivity in Pd-catalyzed allylic alkylation and Ir-catalyzed hydrogenation.[9] So we launched our effort to iridium-catalyzed asymmetric hydrogenation of 3-substituted unsaturated oxindoles under our own catalytic system. Herein, we report an Ir(I)-catalyzed asymmetric hydrogenation approach to chiral C3-mono substituted oxindoles with excellent conversion and up to 93% ee.

* Corresponding author. Tel./fax: +86 21 5474 3265; e-mail address: wanbin@sjtu.edu.cn (W. Zhang).

0040-4020/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2011.09.023

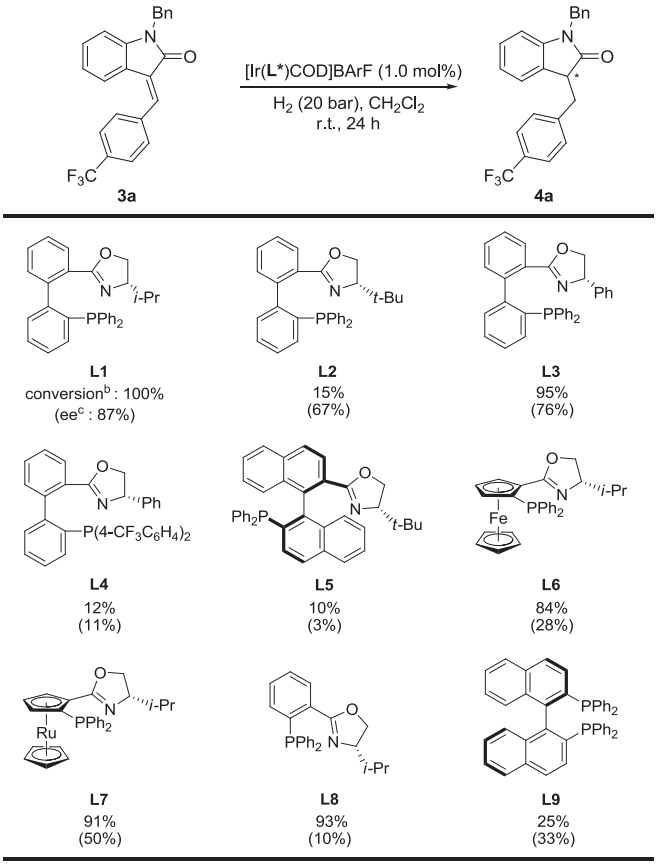


Scheme 1. Complexation behavior of *tropos* chiral phosphine–oxazoline ligands.

2. Results and discussion

We began our investigation using **3a** as the model substrate by 1.0 mol % of the Ir-complex, [Ir(**L***)COD]BArF, in methylene dichloride under 20 bar of H_2 pressure at room temperature for 24 h. The results were summarized in Table 1.

Table 1
Chiral ligand evaluation for asymmetric hydrogenation[a]



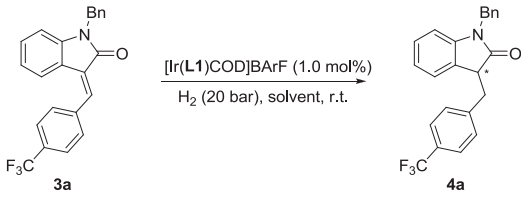
[a] Reaction conditions: **3a** (0.25 mmol), catalyst (1.0 mol %), CH_2Cl_2 (2.0 mL). All of the reactions were carried out under hydrogen at room temperature for 24 h.
[b] The conversion was determined by ^1H NMR spectroscopy.
[c] Enantioselectivities were determined by HPLC using a chiral Daicel Chiralcel AD-H column.

First, under our own catalytic system with *tropos* phosphine-oxazoline ligands **L1**-**L4**, the best result (87% ee with full conversion) was achieved with *i*-Pr-substituted oxazoline ligand **L1**. It is obvious that the substituents on the oxazoline ring played an important role in results of the reaction. When the substituent is *tert*-butyl group, a dramatic drop of conversion and enantioselectivity was observed (only 15% conversion and 67% ee). The electron-poor *tropos* ligand **L4** also gave poor result. Low catalytic reactivity was obtained from the *atropos* phosphine-oxazoline ligand **L5**,[8m] of which the axial chirality is the same as the complexes of *tropos* phosphine-oxazoline ligands **L1**–**L4** coordinated to Ir(I). Those planar chiral P,N-ligands **L6**[10] and **L7**[11] exhibited high conversion but poor enantioselectivities. Then, we tried commercially available chiral ligands PHOX **L8** and BINAP **L9**, neither of them gave good results. We also tried *N*-unprotected and *N*-acetyl 3-substituted unsaturated oxindoles before, but no reaction occurred.

We further performed an investigation on the catalyst counterions with complex [Ir(**L1**)COD]BArF as optimized above. When the counterion of the complex was changed to Cl^- or PF_6^-, the conversions and enantioselectivities were decreased to 9% (0% ee) and 15% (47% ee). Thus, [Ir(**L1**)COD]BArF was used as the catalyst.

Moreover, the effects of solvent and reaction time were evaluated using **3a** as the model substrate employing 1.0 mol % of the [Ir(**L1**)COD]BArF under 20 bar of H_2 pressure at room temperature. The results are summarized in Table 2. At first, the effect of the reaction time was studied. Full conversion of the substrate cost 24 h, shortening the reaction time would hastily lower the conversion although the enantioselectivity nearly remained the same (entries 1–3). Secondly, the effect of solvent was also investigated. It was found that the results of polar solvents were very poor compared with methylene dichloride, toluene, and benzotrifluoride (entries 3–8). Therefore, the optimal conditions are as follows: 1.0 mol % of the Ir-complex, [Ir(**L1**)COD]BArF, in methylene dichloride under 20 bar of H_2 pressure at room temperature for 24 h.

Table 2
The screening of reaction conditions[a]

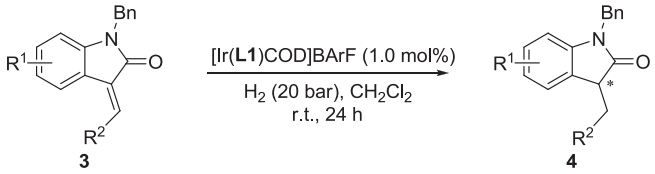


Entry	Solvent	Time (h)	Conversion[b] (%)	ee[c] (%)
1	CH_2Cl_2	1	10	82
2	CH_2Cl_2	3	21	84
3	CH_2Cl_2	24	100	87
4	$PhCH_3$	24	100	86
5	$PhCF_3$	24	100	85
6	MeOH	24	9	2
7	Et_2O	24	22	1
8	THF	24	8	4

[a] Reaction conditions: **3a** (0.25 mmol), catalyst (1.0 mol %), solvent (2.0 mL). All of the reactions were carried out under hydrogen at room temperature.
[b] The conversion was determined by ^1H NMR spectroscopy.
[c] Enantioselectivities were determined by HPLC using a chiral Daicel Chiralcel AD-H column.

Under optimized conditions, a variety of 3-substituted unsaturated oxindoles were hydrogenated to yield their corresponding chiral C3-mono substituted oxindoles (Table 3). The hydrogenation went smoothly with full conversion except for **3b** with (*Z*)-olefin (entry 2) and **3f** with *ortho*-substituted phenyl group as R^2 (entry 7). The hydrogenation appears to be irregular for the steric and electronic nature of the substituent at the phenyl ring

Table 3
Asymmetric hydrogenation of 3-substituted unsaturated oxindoles[a]



3 4

Entry	Substrate	R^1	R^2	Conversion[b] (%)	ee[c] (%)
1	**3a**	H	4-CF_3–C_6H_4	100	87
2	**3b**(*Z*)	H	C_6H_5(*Z*)	65	6
3	**3b**(*E*)	H	C_6H_5(*E*)	100	72
4	**3c**	H	4-MeO–C_6H_4	100	80
5	**3d**	H	4-Me–C_6H_4	100	72
6	**3e**	H	3-Me–C_6H_4	100	82
7	**3f**	H	2-Me–C_6H_4	11	27
8	**3g**	H	1-Naphthyl	100	56
9	**3h**	H	Cyclohexyl	100	86
10	**3i**	H	*i*-Pr	100	82
11	**3j**	H	Et	100	91
12	**3k**	H	Me	100	93
13	**3l**	5-Me	Et	100	88
14	**3m**	5-Me	Cyclohexyl	100	84
15	**3n**	5-F	Cyclohexyl	100	67

[a] Reaction conditions: **3a** (0.25 mmol), catalyst (1.0 mol %), CH_2Cl_2 (2.0 mL). All of the reactions were carried out under hydrogen at room temperature for 24 h.
[b] The conversion was determined by ^1H NMR spectroscopy.
[c] Enantioselectivities were determined by HPLC using a chiral Daicel Chiralcel AD-H column.

of R^2 (entries 1–7). When the R^2 is 1-naphthyl group (**3g**), the asymmetric hydrogenation gave 56% ee (entry 8) due to steric hindrance. For the substrates with aliphatic substituents, the smaller R^2 is, the higher enantioselectivity would be achieved (entries 9–12). Up to 93% ee of hydrogenated product was obtained for **3k** with a methyl group (entry 12), which is the smallest substituent of R^2. We also prepared the substrate 1-benzyl-3-methyleneindolin-2-one, in which R^2 is H, but it is not stable enough to be hydrogenated. In addition, we examined the effect of substituents at the 5-position of oxindole ring (entries 13–15). A slight decrease in enantioselectivity was observed when electron-donating methyl group was introduced as R^1 substituent. And a sharp decrease appeared when R^1 was replaced by electron-withdrawing fluoro group. The racemization experiments of **3k** showed that the chirality of the C3-carbon is stable at 80 °C in toluene for a day, but it racemized very slowly at reflux temperature in toluene from 93% ee to 91% ee after 12 h.

3. Conclusion

In conclusion, we have developed the first metal-catalyzed asymmetric preparation of chiral C3-mono substituted oxindoles by hydrogenation of 3-substituted unsaturated oxindoles with an iridium complex of *tropos* phosphine–oxazoline ligands. The reaction provides efficient access to chiral C3-mono substituted oxindoles with excellent conversion and up to 93% ee.

4. Experimental

4.1. General considerations

All air- and moisture-sensitive manipulations were carried out with standard Schlenk techniques under nitrogen. The reaction solvents were distilled prior to use (toluene, benzotrifluoride, and dichloromethane were distilled from CaH_2, diethyl ether and tetrahydrofuran were distilled from Na, methanol was distilled from Mg). The commercially available reagents were used without further purification. Column chromatography was run on silica gel (100–200 mesh). Melting points were measured on an X-4 microscopic melting point apparatus and were uncorrected. ^1H, ^{13}C NMR spectra were recorded on a Varian MERCURY plus-400 spectrometer. The ee values were determined by HPLC using a Daicel Chiralcel AD-H column. HRMS was performed on a Waters Micromass Q-TOF Premier Mass Spectrometer at the Instrumental Analysis Center of Shanghai Jiao Tong University.

4.2. General procedure for the preparation of 3-substituted unsaturated oxindoles 3

3-Substituted unsaturated oxindoles were synthesized according to the literatures.[12]

*4.2.1. (E)-1-Benzyl-3-(4-(trifluoromethyl)benzylidene)indolin-2-one (**3a**)*[13]. Light yellow oil, 62% yield; ^1H NMR (400 MHz, $CDCl_3$) δ 7.89 (s, 1H), 7.50–7.59 (m, 6H), 7.27–7.36 (m, 5H), 6.87–6.89 (m, 2H), 5.01 (s, 2H).

*4.2.2. (Z)-1-Benzyl-3-benzylideneindolin-2-one (**3b**(Z))*[13]. Light yellow oil, 37% yield; ^1H NMR (400 MHz, $CDCl_3$) δ 8.31 (d, J=4.0 Hz, 1H), 7.60 (s, 1H), 7.54 (d, J=4.0 Hz, 1H), 7.44–7.46 (m, 2H), 7.24–7.33 (m, 8H), 7.18–7.20 (m, 1H), 7.03 (t, J=7.4 Hz, 1H), 6.73 (d, J=8.6 Hz, 1H), 5.00 (s, 2H).

*4.2.3. (E)-1-Benzyl-3-benzylideneindolin-2-one (**3b**(E))*[13]. Light yellow oil, 50% yield; ^1H NMR (400 MHz, $CDCl_3$) δ 7.93 (s, 1H), 7.62–7.67 (m, 2H), 7.44–7.49 (m, 2H), 7.31–7.34 (m, 4H), 7.14 (t, J=7.0 Hz, 1H), 6.84 (t, J=7.6 Hz, 1H), 6.72 (d, J=7.9 Hz, 1H), 5.00 (s, 1H).

*4.2.4. (E)-1-Benzyl-3-(4-methoxybenzylidene)indolin-2-one (**3c**)*[13]. Light yellow oil, 58% yield; ^1H NMR (400 MHz, $CDCl_3$) δ 7.80 (s, 1H), 7.76 (d, J=7.6 Hz, 1H), 7.68 (d, J=8.2 Hz, 2H), 7.28–7.31 (m, 5H), 7.14 (dd, J=7.6, 7.6 Hz, 1H), 7.00 (d, J=8.6 Hz, 2H), 6.88 (dd, J=7.6, 7.6 Hz, 1H), 6.73 (d, J=7.6 Hz, 1H), 5.00 (s, 2H), 3.88 (s, 3H).

*4.2.5. (E)-1-Benzyl-3-(4-methylbenzylidene)indolin-2-one (**3d**)*[13]. Light yellow oil, 53% yield; ^1H NMR (400 MHz, $CDCl_3$) δ 7.91 (s, 1H), 7.71 (d, J=6.9 Hz, 1H), 7.58 (d, J=8.0 Hz, 2H), 7.24–7.33 (m, 5H), 7.21–7.23 (m, 1H), 7.13–7.15 (m, 1H), 6.85–6.67 (m, 1H), 6.74 (d, J=7.9 Hz, 2H), 5.00 (s, 2H), 2.43 (s, 3H).

*4.2.6. (E)-1-Benzyl-3-(3-methylbenzylidene)indolin-2-one (**3e**).* Light yellow oil, 48% yield; ^1H NMR (400 MHz, $CDCl_3$) δ 7.92 (s, 1H), 7.66 (d, J=7.2 Hz, 1H), 7.48–7.50 (m, 2H), 7.24–7.39 (m, 7H), 7.15 (dd, J=7.9, 1.1 Hz, 1H), 6.85 (dd, J=7.9, 1.1 Hz, 1H), 6.73 (d, J=8.0 Hz, 1H), 5.01 (s, 2H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.8, 143.6, 138.6, 138.2, 136.3, 135.1, 130.7, 130.2, 130.0, 129.0, 128.8, 127.8, 127.6, 127.2, 126.6, 123.1, 122.1, 121.6, 109.5, 43.9, 21.6. HRMS (Q-TOF Premier) calcd for $C_{23}H_{19}NO$ $(M+H)^+$: 326.1545; found: 326.1548.

*4.2.7. (E)-1-Benzyl-3-(2-methylbenzylidene)indolin-2-one (**3f**).* Yellow solid, 45% yield, mp 103.3–104.9 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.99 (s, 1H), 7.58 (d, J=7.6 Hz, 1H) 7.24–7.37 (m, 9H), 7.13 (td, J=7.6, 0.8 Hz, 1H), 6.79 (td, J=7.6, 0.8 Hz, 1H), 6.72 (d, J=7.6 Hz, 1H), 5.01 (s, 2H), 2.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.5, 143.4, 137.6, 137.0, 136.4, 136.3, 135.6, 134.4, 131.0, 130.7, 130.3, 130.2, 129.8, 129.6, 129.2, 129.0, 129.0, 128.7, 127.8, 127.7, 127.6, 127.6, 126.0, 125.6, 123.2, 122.1, 121.7, 119.5, 109.3, 109.1, 44.0, 43.7, 20.5, 20.2. HRMS (Q-TOF Premier) calcd for $C_{23}H_{19}NO$ $(M+H)^+$: 326.1545; found: 326.1549.

*4.2.8. (E)-1-Benzyl-3-(naphthalen-1-ylmethylene)indolin-2-one (**3g**).* Yellow solid, 68% yield, mp 156.7–157.8 °C; ^1H NMR

(400 MHz, $CDCl_3$) δ 8.45 (s, 1H), 8.07 (dd, J=7.2, 3.6 Hz, 1H), 7.96 (t, J=8.6 Hz, 2H), 7.85 (d, J=7.2 Hz, 1H), 7.54–7.60 (m, 3H), 7.29–7.42 (m, 5H), 7.20 (d, J=7.2 Hz, 1H), 7.12 (t, J=7.8 Hz, 1H), 6.70–6.75 (m, 2H), 5.06 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.5, 143.6, 136.3, 135.8, 133.8, 132.5, 131.6, 130.2, 129.9, 129.1, 129.0, 128.9, 127.9, 127.6, 127.1, 127.0, 126.8, 125.4, 125.1, 123.4, 122.1, 109.4, 44.1. HRMS (Q-TOF Premier) calcd for $C_{26}H_{19}NO$ $(M+H)^+$: 362.1545; found: 362.1554.

*4.2.9. (E)-1-Benzyl-3-(cyclohexylmethylene)indolin-2-one (**3h**).* Yellow solid, 55% yield; mp 88.8–90.7 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 (d, J=7.2 Hz, 1H), 7.24–7.30 (m, 5H), 7.15 (t, J=7.2 Hz, 1H), 6.98–7.03 (m, 2H), 6.71 (d, J=7.6 Hz, 1H), 4.95 (s, 2H), 2.94–2.97 (m, 1H), 1.74–1.90 (m, 5H), 1.33–1.47 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 147.7, 142.9, 136.4, 128.9, 128.9, 127.7, 127.5, 125.9, 123.6, 122.3, 109.3, 43.8, 38.5, 31.9, 26.0, 25.8. HRMS (Q-TOF Premier) calcd for $C_{22}H_{23}NO$ $(M+H)^+$: 318.1858; found: 318.1854.

*4.2.10. (E)-1-Benzyl-3-(2-methylpropylidene)indolin-2-one (**3i**).* Yellow solid, 62% yield, mp 101.8–102.3 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, J=7.6 Hz, 1H), 7.30 (d, J=4.0 Hz, 4H), 7.24–7.26 (m, 1H), 7.15 (td, J=7.9, 1.1 Hz, 1H), 6.95–7.02 (m, 2H), 6.72 (d, J=7.6 Hz, 1H), 4.96 (s, 2H), 3.24–3.34 (m, 1H), 1.24 (d, J=6.4 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.5, 149.1, 142.9, 136.4, 128.9, 128.9, 127.7, 127.5, 125.8, 123.7, 122.3, 122.3, 109.3, 43.8, 28.8, 22.1. HRMS (Q-TOF Premier) calcd for $C_{19}H_{19}NO$ $(M+H)^+$: 278.1545; found: 278.1547.

*4.2.11. (E)-1-Benzyl-3-propylideneindolin-2-one (**3j**)*[13]. Light yellow oil, 64% yield; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (d, J=7.6 Hz, 1H), 7.16–7.31 (m, 5H), 7.08–7.17 (m, 2H), 7.00 (t, J=7.6 Hz, 1H), 6.71 (d, J=7.6 Hz, 1H), 4.95 (s, 2H), 2.75 (q, J=7.6 Hz, 2H), 1.27 (t, J=7.6 Hz, 3H).

*4.2.12. (E)-1-Benzyl-3-ethylideneindolin-2-one (**3k**)*[13]. Light yellow solid, 51% yield; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, J=7.3 Hz, 1H), 7.28–7.30 (m, 5H), 7.22 (q, J=7.6 Hz, 1H), 7.16 (dd, J=7.9, 7.9 Hz, 1H), 7.01 (dd, J=7.9, 7.9 Hz, 1H), 6.72 (d, J=7.9 Hz, 1H), 4.95 (s, 2H), 2.31 (d, J=7.6 Hz, 3H).

*4.2.13. (E)-1-Benzyl-5-methyl-3-propylideneindolin-2-one (**3l**).* Yellow oil, 70% yield; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (s, 1H), 7.31–7.23 (m, 5H), 7.07 (t, J=7.6 Hz, 1H), 6.96 (d, J=8.0 Hz, 1H), 6.59 (d, J=7.6 Hz, 1H), 4.93 (s, 2H), 2.72 (q, J=7.6 Hz, 2H), 2.32 (s, 3H), 1.27 (t, J=7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.3, 143.9, 140.6, 136.4, 131.6, 129.2, 128.9, 127.6, 127.4, 127.4, 124.5, 122.7, 109.0, 43.8, 23.0, 21.4, 13.3. HRMS (Q-TOF Premier) calcd for $C_{19}H_{19}NO$ $(M+H)^+$: 278.1545; found: 278.1539.

*4.2.14. (E)-1-Benzyl-3-(cyclohexylmethylene)-5-methylindolin-2-one (**3m**).* Yellow solid, 52% yield, mp 75.9–77.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (s, 1H), 7.22–7.29 (m, 5H), 6.95–6.98 (m, 2H), 6.60 (d, J=8.4 Hz, 1H), 4.93 (s, 2H), 2.91–3.00 (m, 1H), 2.33 (s, 3H), 1.74–1.90 (m, 5H), 1.31–1.50 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.6, 147.4, 140.6, 136.4, 131.6, 129.2, 128.9, 127.6, 127.5, 126.0, 124.4, 122.4, 109.0, 43.8, 38.4, 31.9, 26.1, 25.8, 21.6. HRMS (Q-TOF Premier) calcd for $C_{23}H_{25}NO$ $(M+H)^+$: 332.2014; found: 332.2020.

*4.2.15. (E)-1-Benzyl-3-(cyclohexylmethylene)-5-fluoroindolin-2-one (**3n**).* Yellow solid, 46% yield, mp 135.4–136.4 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22–7.33 (m, 6H), 7.04 (d, J=10.0 Hz, 1H), 6.85 (td, J=8.8, 2.4 Hz, 1H), 6.60 (dd, J=8.8, 4.0 Hz, 1H), 4.94 (s, 2H), 2.84–2.91 (m, 1H), 1.74–1.88 (m, 5H), 1.29–1.49 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.2, 160.4, 158.0, 149.7, 137.4, 136.3, 129.0, 127.8, 127.5, 125.1, 125.1, 124.9, 124.8, 114.9, 114.6, 109.5, 109.4, 107.2, 106.9, 43.6, 36.4, 32.5, 26.1, 25.6. HRMS (Q-TOF Premier) calcd for $C_{22}H_{22}FNO$ $(M+H)^+$: 336.1764; found: 336.1742.

4.3. General procedure for the hydrogenation of 3

The catalyst [Ir(**L1**)COD]BArF (4.0 mg, 0.0025 mmol) and substrate **3** (0.25 mmol) were placed in a 5-mL tube equipped with a magnetic stirrer bar. This tube was then put into a nitrogen-filled autoclave. Solvent (2.0 mL) was added to the mixture under a nitrogen atmosphere. The autoclave was then closed, purged three times with hydrogen (less than the pressure needed), and finally pressurized to 20 bar. The reaction mixture was stirred at room temperature for 24 h, and then the hydrogen gas was slowly released. The conversion of the product was determined by ^{1}H NMR spectroscopic analysis of the crude reaction mixture, and the product was purified by chromatography using a petroleum/ethyl acetate mixture (10:1) as eluents. The enantiomeric excess was determined by HPLC on a chiral Daicel Chiralcel AD-H column.

*4.3.1. 1-Benzyl-3-(4-(trifluoromethyl)benzyl)indolin-2-one (**4a**).* Orange solid, mp 118.8–120.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 (d, J=8.8 Hz, 2H), 7.18–7.22 (m, 5H), 7.12 (t, J=7.5 Hz, 1H), 7.06 (d, J=7.1 Hz, 1H), 6.98 (t, J=7.5 Hz, 1H), 6.89–6.91 (m, 2H), 6.56 (d, J=7.9 Hz, 1H), 5.05 (d, J=15.8 Hz, 1H), 4.59 (d, J=15.8 Hz, 1H), 3.88 (dd, J=7.1, 4.3 Hz, 1H), 3.49 (dd, J=13.7, 4.3 Hz, 1H), 3.30 (dd, J=13.7, 7.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.6, 143.6, 141.5, 135.6, 135.0, 131.1, 131.1, 130.3, 129.4, 129.0, 128.8, 128.7, 127.9, 127.7, 127.1, 125.8, 125.3 (t), 124.4, 123.1, 122.5, 109.5, 46.9, 43.8, 36.2. HRMS (Q-TOF Premier) calcd for $C_{23}H_{18}F_3NO$ $(M+H)^+$: 382.1419; found: 382.1410. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 10/90, 1.0 mL min^{-1}, 254 nm): t_R=7.6 and 12.3 min.

*4.3.2. 1,3-Dibenzylindolin-2-one (**4b**)*[14]. Yellow solid, mp 95.3–96.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.24–7.07 (m, 9H), 7.01–6.88 (m, 4H), 6.55 (d, J=7.7 Hz, 1H), 5.04 (d, J=15.8 Hz, 1H), 4.64 (d, J=15.8 Hz, 1H), 3.86 (dd, J=8.1, 4.3 Hz, 1H), 3.51 (dd, J=13.5, 4.3 Hz, 1H), 3.14 (dd, J=13.5, 8.1 Hz, 1H). HPLC (Chiralcel AD-H column, 2-PrOH/hexane 10/90, 1.0 mL min^{-1}, 254 nm): t_R=10.1 and 11.8 min.

*4.3.3. 1-Benzyl-3-(4-methoxybenzyl)indolin-2-one (**4c**).* Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.16–7.21 (m, 4H), 7.09 (t, J=8.0 Hz, 1H), 6.99–7.04 (m, 3H), 6.95 (t, J=8.0 Hz, 1H), 6.87–6.89 (m, 1H), 6.73 (d, J=8.4 Hz, 2H), 6.53 (d, J=7.6 Hz, 1H), 5.06 (d, J=16.4 Hz, 1H), 4.59 (d, J=16.4 Hz, 1H), 3.81 (dd, J=7.7, 4.3 Hz, 1H), 3.77 (s, 3H), 3.43 (dd, J=13.8, 4.3 Hz, 1H), 3.13 (dd, J=13.8, 7.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.2, 158.6, 143.7, 135.7, 130.9, 129.4, 128.8, 128.5, 128.1, 127.5, 127.1, 124.6, 122.3, 113.8, 109.3, 55.3, 47.5, 43.7, 35.8. HRMS (Q-TOF Premier) calcd for $C_{23}H_{21}NO_2$ $(M+H)^+$: 344.1651; found: 344.1642. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 10/90, 1.0 mL min^{-1}, 254 nm): t_R=14.3 and 18.4 min.

*4.3.4. 1-Benzyl-3-(4-methylbenzyl)indolin-2-one (**4d**).* Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.92–7.37 (m, 10H), 6.83 (d, J=8.0 Hz, 1H), 6.72 (d, J=8.0 Hz, 1H), 6.53 (d, J=7.3 Hz, 1H), 5.07 (d, J=4.2 Hz, 1H), 5.03 (d, J=4.8 Hz, 1H), 3.82 (dd, J=8.3, 4.2 Hz, 1H), 3.45 (dd, J=13.9, 4.8 Hz, 1H), 3.01 (dd, J=13.9, 7.6 Hz, 1H), 2.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.2, 143.6, 136.3, 135.8, 134.5, 129.8, 129.2, 128.8, 128.6, 128.1, 127.6, 127.2, 124.7, 122.3, 109.3, 47.4, 43.7, 36.3, 21.4. HRMS (Q-TOF Premier) calcd for $C_{23}H_{21}NO$ $(M+H)^+$: 328.1701; found: 328.1700. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 10/90, 1.0 mL min^{-1}, 254 nm): t_R=9.4 and 12.8 min.

*4.3.5. 1-Benzyl-3-(3-methylbenzyl)indolin-2-one (**4e**).* Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.19–7.22 (m, 3H), 7.07–7.12 (m, 2H),

7.03 (d, J=7.8 Hz, 1H), 6.90–6.97 (m, 6H), 6.55 (d, J=7.8, 1H), 5.05 (d, J=15.8 Hz, 1H), 4.64 (d, J=15.8 Hz, 1H), 3.84 (dd, J=8.4, 4.2 Hz, 1H), 3.48 (dd, J=13.4, 4.2 Hz, 1H), 3.07 (dd, J=13.4, 8.4 Hz, 1H), 2.25 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.5, 143.5, 137.0, 136.7, 136.1, 130.8, 130.3, 129.0, 128.8, 128.1, 127.7, 127.4, 127.1, 126.1, 125.0, 122.3, 109.2, 46.0, 43.9, 34.5, 19.9. HRMS (Q-TOF Premier) calcd for $C_{23}H_{21}NO$ $(M+H)^+$: 328.1701; found: 328.1700. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.8 mL min^{-1}, 254 nm): t_R=12.8 and 15.5 min.

*4.3.6. 1-Benzyl-3-(2-methylbenzyl)indolin-2-one (**4f**).* Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.10–7.32 (m, 10H), 6.86 (td, J=7.4, 1.0 Hz, 1H), 6.68 (t, J=7.4 Hz, 2H), 5.00 (d, J=15.6 Hz, 1H), 4.85 (d, J=15.6 Hz, 1H), 3.81 (dd, J=10.0, 4.4 Hz, 1H), 3.57 (dd, J=14.0, 4.4 Hz, 1H), 2.92 (dd, J=14.0, 10.0 Hz, 1H), 2.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.5, 143.5, 137.0, 136.7, 136.1, 130.8, 130.4, 129.0, 128.8, 128.1, 127.8, 127.4, 127.1, 126.1, 125.0, 122.3, 109.2, 46.1, 43.9, 34.5, 20.0. HRMS (Q-TOF Premier) calcd for $C_{23}H_{21}NO$ $(M+H)^+$: 328.1701; found: 328.1697. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 9/91, 0.9 mL min^{-1}, 254 nm): t_R=11.9 and 12.7 min.

*4.3.7. 1-Benzyl-3-(naphthalen-1-ylmethyl)indolin-2-one (**4g**).* Yellow solid, mp 99.1–100.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.32 (d, J=8.8 Hz, 1H), 7.92 (d, J=8.0 Hz, 1H), 7.84 (d, J=8.0 Hz, 1H), 7.52–7.61 (m, 2H), 7.42 (t, J=7.6 Hz, 1H), 7.25–7.33 (m, 6H), 7.11 (t, J=7.6 Hz, 1H), 6.81 (td, J=7.6, 0.8 Hz, 1H), 6.71 (d, J=8.0 Hz, 1H), 6.51 (d, J=7.6 Hz, 1H), 5.01 (d, J=15.6 Hz, 1H), 4.90 (d, J=15.6 Hz, 1H), 4.19 (dd, J=14.3, 3.9 Hz, 1H), 3.98 (dd, J=10.6, 3.9 Hz, 1H), 3.12 (dd, J=14.3, 10.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.6, 143.5, 136.1, 134.5, 134.3, 131.9, 129.2, 129.0, 128.2, 128.0, 127.8, 127.5, 126.6, 126.1, 125.4, 125.3, 124.0, 122.2, 109.2, 46.1, 44.0, 35.3. HRMS (Q-TOF Premier) calcd for $C_{26}H_{21}NO$ $(M+H)^+$: 364.1701; found: 364.1689. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.8 mL min^{-1}, 254 nm): t_R=18.1 and 19.1 min.

*4.3.8. 1-Benzyl-3-(cyclohexylmethyl)indolin-2-one (**4h**).* Ivory solid, mp 64.9–65.6 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22–7.32 (m, 6H), 7.15 (t, J=8.3 Hz, 1H), 7.00 (t, J=7.4 Hz, 1H), 6.72 (d, J=8.0 Hz, 1H), 4.97 (d, J=15.6 Hz, 1H), 4.84 (d, J=15.6 Hz, 1H), 3.58 (t, J=6.6 Hz, 1H), 1.87–1.94 (m, 1H), 1.14–1.81 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.7, 141.0, 136.3, 131.9, 130.1, 128.9, 128.0, 127.7, 127.5, 125.2, 108.9, 43.8, 43.3, 39.0, 34.8, 33.9, 33.1, 26.7, 26.4, 21.4. HRMS (Q-TOF Premier) calcd for $C_{22}H_{25}NO$ $(M+H)^+$: 320.2014; found: 320.2018. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 9/91, 0.8 mL min^{-1}, 254 nm): t_R=10.7 and 11.9 min.

*4.3.9. 1-Benzyl-3-isobutylindolin-2-one (**4i**).* Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25–7.34 (m, 6H), 7.15–7.19 (m, 1H), 7.01 (t, J=7.8 Hz, 1H), 6.74 (d, J=8.0 Hz, 1H), 4.96 (d, J=15.6 Hz, 1H), 4.88 (d, J=15.6 Hz, 1H), 3.57 (t, J=7.2 Hz, 1H), 2.05–2.12 (m, 1H), 1.88–1.95 (m, 1H), 1.67–1.74 (m, 1H), 1.02 (dd, J=17.6, 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.6, 143.5, 136.3, 129.9, 128.9, 127.9, 127.8, 127.6, 124.4, 122.4, 109.3, 44.0, 40.5, 25.6, 23.2, 22.4. HRMS (Q-TOF Premier) calcd for $C_{19}H_{21}NO$ $(M+H)^+$: 280.1701; found: 280.1701. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.6 mL min^{-1}, 254 nm): t_R=14.0 and 15.4 min.

*4.3.10. 1-Benzyl-3-propylindolin-2-one (**4j**).* Ivory solid, mp 62.6–63.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.24–7.32 (m, 6H), 7.15 (t, J=7.6 Hz, 1H), 7.01 (t, J=7.6 Hz, 1H), 6.70 (d, J=7.6 Hz, 1H), 4.97 (d, J=15.6 Hz, 1H), 4.85 (d, J=15.6 Hz, 1H), 3.54 (t, J=6.0 Hz, 1H), 1.90–2.06 (m, 2H), 1.33–1.51 (m, 2H), 0.94 (t, J=7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.3, 143.7, 136.3, 129.5, 129.0, 127.9, 127.7, 127.5, 124.1, 122.5, 109.2, 45.7, 43.9, 33.2, 19.4, 14.3. HRMS (Q-TOF Premier) calcd for $C_{18}H_{19}NO$ $(M+H)^+$: 266.1545; found: 266.1546. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.5 mL min^{-1}, 254 nm): t_R=16.9 and 20.0 min.

*4.3.11. 1-Benzyl-3-ethylindolin-2-one (**4k**).* Ivory solid, mp 79.5–80.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23–7.32 (m, 6H), 7.16 (t, J=7.6 Hz, 1H), 7.02 (td, J=7.6, 0.8 Hz, 1H), 6.71 (d, J=7.6 Hz, 1H), 5.00 (d, J=15.6 Hz, 1H), 4.84 (d, J=15.6 Hz, 1H), 3.52 (t, J=5.8 Hz, 1H), 2.05–2.11 (m, 2H), 0.92 (t, J=7.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.1, 146.6, 136.2, 129.1, 128.9, 127.9, 127.7, 127.5, 124.1, 122.5, 109.1, 46.8, 43.9, 24.0, 10.3. HRMS (Q-TOF Premier) calcd for $C_{17}H_{17}NO$ $(M+H)^+$: 252.1388; found: 252.1388. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.6 mL min^{-1}, 254 nm): t_R=15.1 and 16.8 min.

*4.3.12. 1-Benzyl-5-methyl-3-propylindolin-2-one (**4l**).* Yellow solid, mp 60.8–61.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23–7.31 (m, 5H), 7.07 (s, 1H), 6.94 (d, J=7.6 Hz, 1H), 6.58 (d, J=7.6 Hz, 1H), 4.95 (d, J=15.6 Hz, 1H), 4.83 (d, J=15.6 Hz, 1H), 3.50 (t, J=6.2 Hz, 1H), 2.30 (s, 3H), 1.92–2.04 (m, 2H), 1.32–1.49 (m, 2H), 0.94 (t, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.3, 141.3, 136.4, 132.0, 129.6, 128.9, 128.1, 127.7, 127.5, 125.0, 108.9, 45.8, 43.9, 33.2, 21.3, 19.4, 14.3. HRMS (Q-TOF Premier) calcd for $C_{19}H_{21}NO$ $(M+H)^+$: 280.1701; found: 280.1718. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.5 mL min^{-1}, 254 nm): t_R=17.3 and 24.0 min.

*4.3.13. 1-Benzyl-3-(cyclohexylmethyl)-5-methylindolin-2-one (**4m**).* Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22–7.32 (m, 5H), 7.03 (d, J=0.8 Hz, 1H), 6.95 (dt, J=8.4, 0.8 Hz, 1H), 6.59 (d, J=8.4 Hz, 1H), 4.94 (d, J=15.6 Hz, 1H), 4.82 (d, J=15.6 Hz, 1H), 3.54 (t, J=6.6 Hz, 1H), 2.31 (s, 3H), 1.86–1.94 (m, 1H), 1.66–1.81 (m, 6H), 1.12–1.33 (m, 4H), 0.93–1.04 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.7, 141.1, 136.4, 131.8, 130.2, 128.9, 128.0, 127.7, 127.5, 125.2, 108.9, 43.9, 43.3, 39.0, 34.8, 33.9, 33.2, 26.8, 26.4, 21.4. HRMS (Q-TOF Premier) calcd for $C_{23}H_{27}NO$ $(M+H)^+$: 334.2171; found: 334.2163. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.5 mL min^{-1}, 254 nm): t_R=16.4 and 21.2 min.

*4.3.14. 1-Benzyl-3-(cyclohexylmethyl)-5-fluoroindolin-2-one (**4n**).* White solid, mp 74.5–75.4 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.24–7.33 (m, 5H), 6.95–6.98 (m, 1H), 6.84 (dt, J=8.7, 2.4 Hz, 1H), 6.60 (dd, J=8.7, 4.6 Hz, 1H), 4.95 (d, J=15.6 Hz, 1H), 4.82 (d, J=15.6 Hz, 1H), 3.58 (t, J=6.8 Hz, 1H), 1.88–1.95 (m, 1H), 1.62–1.78 (m, 7H), 1.15–1.28 (m, 3H), 0.93–1.04 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.3, 160.4, 158.0, 153.2, 139.3, 136.0, 131.7, 131.6, 129.0, 127.9, 127.5, 114.1, 113.9, 112.6, 112.3, 109.6, 109.5, 44.0, 43.6, 38.7, 34.8, 33.9, 33.1, 26.6, 26.3. HRMS (Q-TOF Premier) calcd for $C_{22}H_{24}FNO$ $(M-H)^+$: 336.1769; found: 336.1760. HPLC (Chiralcel AD-H column, 2-PrOH/hexane 8/92, 0.5 mL min^{-1}, 254 nm): t_R=19.4 and 25.5 min.

Acknowledgements

This work was supported by the National Nature Science Foundation of China (No. 20872091 and 20972095), Science and Technology Commission of Shanghai Municipality (No. 09JC1407800), Shanghai Jiao Tong University (interdisciplinary fund) and Nippon Chemical Industrial Co., Ltd. We thank Professor T. Imamoto and Dr. M. Sugiya for the helpful discussion and Instrumental Analysis Center of Shanghai Jiao Tong University.

References and notes

1. For reviews: (a) Galliford, C. V.; Scheidt, K. A. *Angew. Chem., Int. Ed.* **2007**, *46*, 8748; (b) Marti, C.; Carreira, E. M. *Eur. J. Org. Chem.* **2003**, 2209; (c) Hibino, S.; Choshi, T. *Nat. Prod. Rep.* **2001**, *18*, 66.
2. For examples: (a) Li, P.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2011**, *50*, 6396; (b) Jaegli, J.; Dufour, J.; Wei, H.-L.; Piou, T.; Duan, X.-H.; Vors, J.-P.; Neuville, L.; Zhu,

J. *Org. Lett.* **2010**, *12*, 4498; (c) An, G.; Zhou, W.; Zhang, G.; Sun, H.; Han, J.; Pan, Y. *Org. Lett.* **2010**, *12*, 4482; (d) Klein, J. E. M. N.; Perry, A.; Pugh, D. S.; Taylor, R. J. K. *Org. Lett.* **2010**, *12*, 3446; (e) Jia, Y.-X.; Kundig, E. P. *Angew. Chem., Int. Ed.* **2009**, *48*, 1636; (f) Ruck, R. T.; Huffman, M. A.; Kim, M. M.; Shevlin, M.; Kandur, W. V.; Davies, I. W. *Angew. Chem., Int. Ed.* **2008**, *47*, 4711; (g) Movassaghi, M.; Schmidt, M. A.; Ashenhurst, J. A. *Org. Lett.* **2008**, *10*, 4009; (h) Li, C.; Chan, C.; Heimann, A. C.; Danishefsky, S. J. *Angew. Chem., Int. Ed.* **2007**, *46*, 1444; (i) Guo, X.; Huang, H.; Yang, L.; Hu, W. *Org. Lett.* **2007**, *9*, 4721; (j) Yong, S. R.; Ung, A. T.; Pyne, S. G.; Skelton, B. W.; White, A. H. *Tetrahedron* **2007**, *63*, 5579; (k) Feldman, K. S.; Karatjas, A. G. *Org. Lett.* **2006**, *8*, 4137; (l) Nakamura, T.; Shirokawa, S.; Hosokawa, S.; Nakazaki, A.; Kobayashi, S. *Org. Lett.* **2006**, *8*, 677; (m) Cravotto, G.; Giovenzana, G. B.; Palmisano, G.; Penoni, A.; Pilati, T.; Sisti, M.; Stazi, F. *Tetrahedron: Asymmetry* **2006**, *17*, 3070; (n) Huang, A.; Kodanko, J. J.; Overman, L. E. *J. Am. Chem. Soc.* **2004**, *126*, 14043; (o) Kawasaki, T.; Nagaoka, M.; Satoh, T.; Okamoto, A.; Ukon, R.; Ogawa, A. *Tetrahedron* **2004**, *60*, 3493; (p) Lizos, D. E.; Murphy, J. A. *Org. Biomol. Chem.* **2003**, *1*, 117; (q) Lizos, D.; Tripoli, R.; Murphy, J. A. *Chem. Commun.* **2001**, 2732; (r) Cravotto, G.; Giovenzana, G. B.; Pilati, T.; Sisti, M.; Palmisano, G. *J. Org. Chem.* **2001**, *66*, 8447; (s) Hilton, S. T.; Ho, T. C. T.; Pljevaljcic, G.; Jones, K. *Org. Lett.* **2000**, *2*, 2639.

3. (a) Yin, L.; Kanai, M.; Shibasaki, M. *Angew. Chem., Int. Ed.* **2011**, *50*, 7620; (b) Shen, K.; Liu, X.; Wang, G.; Lin, L.; Feng, X. *Angew. Chem., Int. Ed.* **2011**, *50*, 4684; (c) Zhang, Z.; Zheng, W.; Antilla, J. C. *Angew. Chem., Int. Ed.* **2011**, *50*, 1135; (d) Zhou, F.; Liu, Y.-L.; Zhou, J. *Adv. Synth. Catal.* **2010**, *353*, 1381; (e) Hanhan, N. V.; Sahin, A. H.; Chang, T. W.; Fettinger, J. C.; Franz, A. K. *Angew. Chem., Int. Ed.* **2010**, *49*, 744; (f) Mouri, S.; Chen, Z.; Mitsunuma, H.; Furutachi, M.; Matsunaga, S.; Shibasaki, M. *J. Am. Chem. Soc.* **2010**, *132*, 1255; (g) Tomita, D.; Yamatsugu, K.; Kanai, M.; Shibasaki, M. *J. Am. Chem. Soc.* **2009**, *131*, 6946; (h) Jia, Y.-X.; Hillgren, J. M.; Watson, E. L.; Marsden, S. P.; Kundig, E. P. *Chem. Commun.* **2008**, 4040; (i) Trost, B. M.; Brennan, M. K. *Org. Lett.* **2006**, *8*, 2027; (j) Ishimaru, T.; Shibata, N.; Nagai, J.; Nakamura, S.; Toru, T.; Kanemasa, S. *J. Am. Chem. Soc.* **2006**, *128*, 16488; (k) Shintani, R.; Inoue, M.; Hayashi, T. *Angew. Chem., Int. Ed.* **2006**, *45*, 3353; (l) Toullec, P. Y.; Jagt, R. B. C.; de Vries, J. G.; Feringa, B. L.; Minnaard, A. J. *Org. Lett.* **2006**, *8*, 2715; (m) Hamashima, Y.; Suzuki, T.; Takano, H.; Shimura, Y.; Sodeoka, M. *J. Am. Chem. Soc.* **2005**, *127*, 10164.
4. (a) Zhu, Q.; Lu, Y. *Angew. Chem., Int. Ed.* **2010**, *49*, 7753; (b) Jiang, X.; Cao, Y.; Wang, Y.; Liu, L.; Shen, F.; Wang, R. *J. Am. Chem. Soc.* **2010**, *132*, 15328; (c) Liao, Y.-H.; Liu, X.-L.; Wu, Z.-J.; Cun, L.-F.; Zhang, X.-M.; Yuan, W.-C. *Org. Lett.* **2010**, *12*, 2896; (d) Cheng, L.; Liu, L.; Jia, H.; Wang, D.; Chen, Y.-J. *J. Org. Chem.* **2009**, *74*, 4650; (e) Galzerano, P.; Bencivenni, G.; Pesciaioli, F.; Mazzanti, A.; Giannichi, B.; Sambri, L.; Bartoli, G.; Melchiorre, P. *Chem.—Eur. J.* **2009**, *15*, 7846; (f) He, R.; Ding, C.; Maruoka, K. *Angew. Chem., Int. Ed.* **2009**, *48*, 4559; (g) Duffey, T. A.; Shaw, S. A.; Vedejs, E. *J. Am. Chem. Soc.* **2009**, *131*, 14; (h) Jiang, K.; Peng, J.; Cui, H.-L.; Chen, Y.-C. *Chem. Commun.* **2009**, 3955; (i) Cheng, L.; Liu, L.; Jia, H.; Wang, D.; Chen, Y.-J. *Org. Lett.* **2009**, *11*, 3874; (j) Ishimaru, T.; Shibata, N.; Horikawa, T.; Yasuda, N.; Nakamura, S.; Toru, T.; Shiro, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4157; (k) Tian, X.; Jiang, K.; Peng, J.; Du, W.; Chen, Y.-C. *Org. Lett.* **2008**, *10*, 3583; (l) Sano, D.; Nagata, K.; Itoh, T. *Org. Lett.* **2008**, *10*, 1593; (m) Nakamura, S.; Hara, N.; Nakashima, H.; Kubo, K.; Shibata, N.; Toru, T. *Chem.—Eur. J.* **2008**, *14*, 8079; (n) Ogawa, S.; Shibata, N.; Inagaki, J.; Nakamura, S.; Toru, T.; Shiro, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 8666; (o) Shaw, S. A.; Aleman, P.; Christy, J.; Kampf, J. W.; Va, P.; Vedejs, E. *J. Am. Chem. Soc.* **2006**, *128*, 925; (p) Luppi, G.; Cozzi, P. G.; Monari, M.; Kaptein, B.; Broxterman, Q. B.; Tomasini, C. *J. Org. Chem.* **2005**, *70*, 7418; (q) Bella, M.; Kobbelgaard, S.; Jorgensen, K. A. *J. Am. Chem. Soc.* **2005**, *127*, 3670; (r) Hills, I. D.; Fu, G. C. *Angew. Chem., Int. Ed.* **2003**, *42*, 3921.
5. For examples: (a) Tietze, L. F.; Schmuck, K.; Schuster, H. J.; Muller, M.; Schuberth, I. *Chem.—Eur. J.* **2011**, *17*, 1922; (b) Tietze, L. F.; Krewer, B.; Major, F.; Schuberth, I. *J. Am. Chem. Soc.* **2009**, *131*, 13031; (c) Tichenor, M. S.; MacMillan, K. S.; Trzupek, J. D.; Rayl, T. J.; Hwang, I.; Boger, D. L. *J. Am. Chem. Soc.* **2007**, *129*, 10858; (d) Jin, W.; Trzupek, J. D.; Rayl, T. J.; Broward, M. A.; Vielhauer, G. A.; Weir, S. J.; Hwang, I.; Boger, D. L. *J. Am. Chem. Soc.* **2007**, *129*, 15391; (e) Stratmann, K.; Moore, R. E.; Bonjouklian, R.; Deeter, J. B.; Patterson, G. M. L.; Shaffer, S.; Smith, C. D.; Smitkat, T. A. *J. Am. Chem. Soc.* **1994**, *116*, 9935.
6. Curran, D. P.; Liu, W.; Chen, C. H.-T. *J. Am. Chem. Soc.* **1999**, *121*, 11012.
7. (a) Xie, J.-H.; Zhu, S.-F.; Zhou, Q.-L. *Chem. Rev.* **2011**, *111*, 1713; (b) Roseblade, S. J.; Pfaltz, A. *Acc. Chem. Res.* **2007**, *40*, 1402.
8. For reviews: (a) Hargaden, G. C.; Guiry, P. J. *Chem. Rev.* **2009**, *109*, 1089; (b) Dai, Y.; Yang, G.; Zhang, Y. J.; Wang, F.; Zhang, W. *Chin. J. Org. Chem.* **2008**, *28*, 1169; (c) McManus, H. A.; Guiry, P. J. *Chem. Rev.* **2004**, *104*, 4151; (d) for selected papers: Zhao, Q.-Y.; Yuan, Z.-L.; Shi, M. *Tetrahedron: Asymmetry* **2010**, *21*, 943; (e) Dotta, P.; Kumar, P. A.; Pregosin, P.; Albinati, A.; Rizzato, S. *Organometallics* **2004**, *23*, 2295; (f) Hatano, M.; Yamanaka, M.; Mikami, K. *Eur. J. Org. Chem.* **2003**, 2552; (g) Hayashi, T.; Okada, A.; Suzuka, T.; Kawatsura, M. *Org. Lett.* **2003**, *5*, 1713; (h) Hatano, M.; Mikami, K. *Org. Biomol. Chem.* **2003**, *1*, 3871; (i) Dotta, P.; Magistrato, A.; Rothlisberger, U.; Pregosin, P.; Albinati, A. *Organometallics* **2002**, *21*, 3033; (j) Selvakumar, K.; Valentini, M.; Pregosin, P.; Albinati, A. *Organometallics* **1999**, *18*, 4591; (k) Selvakumar, K.; Valentini, M.; Wrle, M.; Pregosin, P.; Albinati, A. *Organometallics* **1999**, *18*, 1207; (l) Ogasawara, M.; Yoshida, K.; Kamei, H.; Kato, K.; Uozumi, Y.; Hayashi, T. *Tetrahedron: Asymmetry* **1998**, *9*, 1779; (m) Imai, Y.; Zhang, W.; Kida, T.; Nakatsuji, Y.; Ikeda, I. *Tetrahedron Lett.* **1998**, *39*, 4343.
9. (a) Yao, D.; Tian, F.; Zhang, W. *Chin. J. Org. Chem.* **2011**, *31*, 505; (b) Liu, Y.; Yang, G.; Yao, D.; Tian, F.; Zhang, W. *Sci. China: Chem.* **2011**, *54*, 87; (c) Tian, F.; Yao, D.; Liu, Y.; Zhang, W. *Adv. Synth. Catal.* **2010**, *352*, 1841; (d) Tian, F.; Yao, D.; Zhang, Y.-J.; Zhang, W. *Tetrahedron* **2009**, *65*, 9609; (e) Zhang, W.; Xie, F.; Yoshinaga, H.; Kida, T.; Nakatsuji, Y.; Ikeda, I. *Synlett* **2006**, 1185.
10. (a) Zhang, W.; Hirao, T.; Ikeda, I. *Tetrahedron Lett.* **1996**, *37*, 4545; (b) Nishibayashi, Y.; Uemura, S. *Synlett* **1995**, 79; (c) Richards, C. J.; Damalidis, T.; Hibbs, D. E.; Hursthouse, M. B. *Synlett* **1995**, 74.
11. (a) Zhao, X.; Liu, D.; Xie, F.; Liu, Y.; Zhang, W. *Org. Biomol. Chem.* **2011**, *9*, 1871; (b) Zhao, X.; Liu, D.; Xie, F.; Zhang, W. *Tetrahedron* **2009**, *65*, 512; (c) Wang, Y.; Liu, D.; Meng, Q.; Zhang, W. *Tetrahedron: Asymmetry* **2009**, *20*, 2510; (d) Liu, D.; Xie, F.; Zhao, X.; Zhang, W. *Tetrahedron* **2008**, *64*, 3561; (e) Xie, F.; Liu, D.; Zhang, W. *Tetrahedron Lett.* **2008**, *49*, 1012; (f) Liu, D.; Xie, F.; Zhang, W. *Tetrahedron Lett.* **2007**, *48*, 7591.
12. (a) Ji, L.; Fang, Q.; Yuan, M.-S.; Liu, Z.-Q.; Shen, Y.-X.; Chen, H.-F. *Org. Lett.* **2010**, *12*, 5192; (b) Tang, P.; Su, Y.; Feng, J.; Fu, J.; Yang, J.; Xiao, L.; Peng, J.; Li, Y.; Zhang, L.; Hu, B.; Zhou, Y.; Li, F.; Fu, B.; Lou, L.; Gong, A.; She, G.; Sun, W.; Mong, X. *J. Med. Chem.* **2010**, *53*, 8140; (c) Itoh, T.; Ishikawa, H.; Hayashi, Y. *Org. Lett.* **2009**, *11*, 3854; (d) Nozoye, T.; Nakai, T.; Kubo, A. *Chem. Pharm. Bull.* **1977**, *25*, 196.
13. Yanada, R.; Obika, S.; Kobayashi, Y.; Inokuma, T.; Oyama, M.; Yanada, K.; Takemoto, Y. *Adv. Synth. Catal.* **2005**, *347*, 1632.
14. Trost, B. M.; Zhang, Y. *Chem.—Eur. J.* **2011**, *17*, 2916.