Full Paper

Applied Organometallic Chemistry

Received: 11 January 2009 Accepted: 3 February 2009 Published online in Wiley Interscience: 19 March 2009

(www.interscience.com) DOI 10.1002/aoc.1491

Preparation of novel axially chiral NHC–Pd(II) complexes and their application in oxidative kinetic resolution of secondary alcohols

Shi-Jia Liu[a], Lian-jun Liu[a] and Min Shi[a,b]*

Novel axially chiral *N*-heterocyclic carbene (NHC) Pd(II) complexes were prepared from optically active 1,1′-binaphthalenyl-2,2′-diamine (BINAM) and H_8-BINAM and their crystal structures were unambiguously determined by X-ray diffraction. These chiral *N*-heterocyclic carbene (NHC) Pd(II) complexes were applied in the oxidative kinetic resolution of secondary alcohols using molecular oxygen as a terminal oxidant or under aerobic conditions, affording the corresponding *sec*-alcohols in good yields with moderate to good enantioselectivities.

Supporting information may be found in the online version of this article.

Keywords: axially chiral NHC-Pd(II) complex; 1,1′-binaphthalenyl-2,2′-diamine (BINAM); H_8-BINAM; X-ray diffraction; oxidative kinetic resolution of secondary alcohols

Introduction

The use of *N*-heterocyclic carbene (NHC) ligands has developed rapidly in the latest decade due to their stability to air and moisture, and their strong σ-donor but poor π-acceptor abilities.[1] Homogeneous catalytic reactions using NHC–Pd complexes have been extensively investigated and some excellent results have been achieved.[2] Moreover, the asymmetric catalysis using a variety of chiral NHC–Pd complexes has also made significant progress during the last several years.[3] For example, the application of chiral NHC–Pd(II) complexes in enantioselective kinetic resolution of secondary alcohols has been disclosed recently.[4] In addition, we previously also reported that axially chiral *N*-heterocyclic carbene (NHC) Pd(II) complexes **A** and **B** could be prepared from optically active 1,1′-binaphthalenyl-2,2′-diamine (BINAM) and H_8-BINAM, and these interesting chiral Pd(II) catalysts could be applied in the oxidative kinetic resolution of secondary alcohols using molecular oxygen as a terminal oxidant, affording the corresponding *sec*-alcohols in good yields with moderate to good enantioselectivities (Fig. 1).[5] In this paper, we wish to report the preparation of two novel axially chiral *N*-heterocyclic carbene (NHC) Pd(II) complexes **1a** and **1b** (Fig. 1) and their X-ray crystal data along with the results in the enantioselective kinetic resolution of secondary alcohols using molecular oxygen as a terminal oxidant.

Results and Discussion

As show in Scheme 1, starting from optically active (*R*)-1,1-binaphthalenyl-2,2′-diamine **2** [(*R*)-BINAM] and following our previously reported procedures,[6] we can easily obtain the compounds **4–6** in good yields. The detailed spectroscopic data of **4–6** are summarized in the Supporting Information. The corresponding dibenzimidazolium iodides (NHC precursors) **7a–c** were obtained from the reaction of ethyl iodide, benzyl iodide or 3,5-dimethylbenzyl iodide with **6** in acetonitrile under reflux in good yields (Scheme 1). Upon treatment of **7a–c** with $Pd(OAc)_2$ under reflux in tetrahydrofuran (THF) for 16 h, the corresponding NHC–Pd(II) complexes **1a** and **1b** were obtained in 87 and 78% yields, respectively, although NHC–Pd(II) complex **1c** was formed in low yield (10% yield), presumably due to the sterical factor (Scheme 1). Since **1c** was obtained in low yield, we did not use it for further investigation.

These NHC–Pd(II) complexes **1a** and **1b** are air and moisture stable in the solid state and even in the solution state. Their structures were assigned by IR, ^{1}H NMR spectroscopic data and ESI-MS spectroscopy as well as microanalyses. The crystal structures of **1a** and **1b** were further unambiguously determined by X-ray diffraction.[1] (The crystal data of **1a** have been deposited in CCDC with number 666 584. Empirical formula, $C_{42}H_{38}I_2N_4O_2Pd$; formula weight, 990.96; crystal size, 0.459 × 0.347 × 0.213; crystal color, habit, colorless, prismatic; crystal system, orthorhombic; lattice type, primitive; lattice parameters: a = 10.3207(9) Å, b = 13.5057(12) Å, c = 28.682(3) Å, α = 90°, β = 90°, γ = 90°, V = 3997.9(6) Å^3; space group, P2(1)2(1)2(1); Z = 4; D_{calc} = 1.646 g cm^{-3}; F_{000} = 1944; R_1 = 0.0458, wR_2 = 0.0938. Diffractometer: Rigaku AFC7R. The crystal data of **1b** have been deposited in CCDC with number 689 592. Empirical formula, $C_{48}H_{34}I_2N_4Pd$; formula weight, 1026.99; crystal size, 0.176 ×

* *Correspondence to: Min Shi, Laboratory for Advanced Materials and Institute of Fine Chemicals, School of Chemistry & Molecular Engineering, East China University of Science and Technology, 130 Mei Long Road, Shanghai 200237, People's Republic of China. E-mail: Mshi@mail.sioc.ac.cn*

a *Laboratory for Advanced Materials and Institute of Fine Chemicals, School of Chemistry and Molecular Engineering, East China University of Science and Technology, 130 Mei Long Road, Shanghai 200237, People's Republic of China*

b *State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 354 Fenglin Road, Shanghai 200032, People's Republic of China*

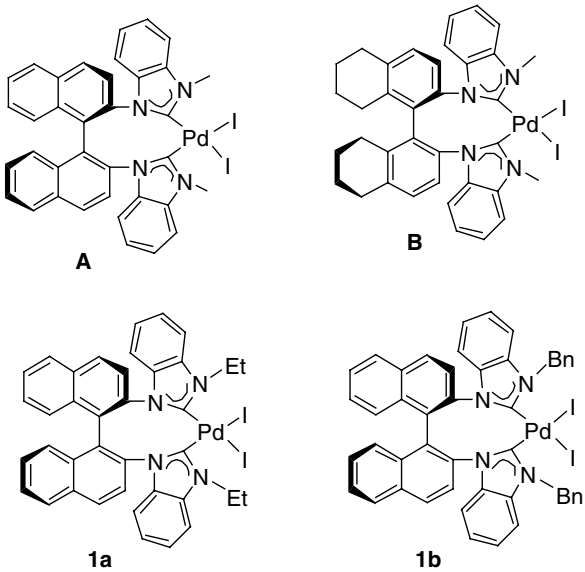


Figure 1. Axially chiral *N*-heterocyclic carbene (NHC)–Pd(II) complexes **A, B, 1a** and **1b**.

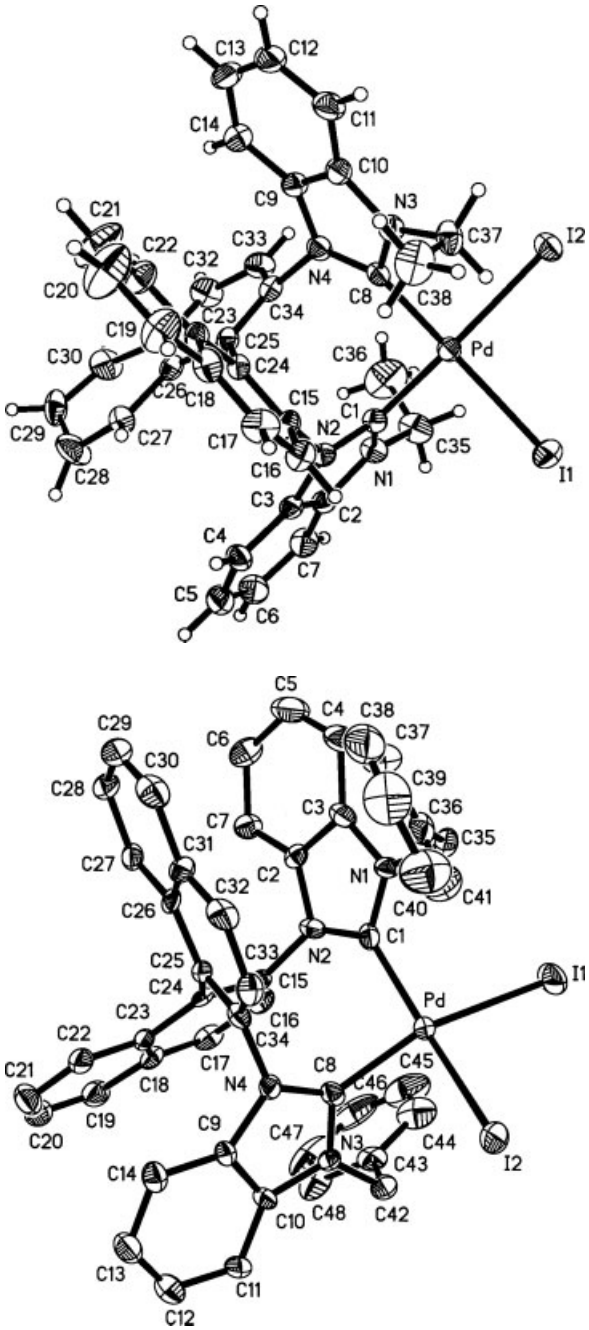


Figure 2. ORTEP drawing of NHC–Pd(II) complexes **1a** and **1b**.

0.091 × 0.076; crystal color, habit, colorless, prismatic; crystal system, orthorhombic; lattice type, primitive; lattice parameters: $a = 9.4239(5)$ Å, $b = 19.2103(11)$ Å, $c = 22.8716(13)$ Å, $\alpha = 90^\circ$, $\beta = 90^\circ$, $\gamma = 90^\circ$, $V = 4140.6(4)$ Å^3; space group, P2(1)2(1)2(1); $Z = 4$; $D_{calc} = 1.647$ g cm^{-3}; $F_{000} = 2008$; $R_1 = 0.0540$, $wR_2 = 0.0901$. Diffractometer, Rigaku AFC7R.) Single crystals of these complexes suitable for X-ray crystal structure analysis were grown from mixed solvent petroleum ether–CH_2Cl_2 (2 : 3). Figure 1 depicts the X-ray crystal structures of NHC–Pd(II) complexes **1a** and **1b**. They have very similar crystal structures. The crystal structures of **1a** and **1b** revealed a distorted-square-planar geometry around the metal center. The NHC ligand and iodide anion ligand coordinate to the palladium center, respectively, stabilizing a 16-electron configuration around the metal center. The bite angles of C–Pd–C in complexes **1a** and **1b** are 95.2(2) and 96.3(3), respectively, which are slightly more than 90° (96.3°) with small deviations from idealized square planar geometry. Selected bond distances (Å) and angles (deg) of (NHC)–Pd(II) complexes of **1a** and **1b** are summarized in Tables 1 and 2, respectively. These are NHC *cis*-chelating, bidentate Pd(II) complexes. The bond lengths of Pd–C(1) and Pd–C(8) [1.9846(3) and 2.004(5) Å in complex **1a** as well as Pd–C(1) = 1.997(8) and Pd–C(8) = 2.008(7) in complex **1b**] are comparable to those of analogs.[7]

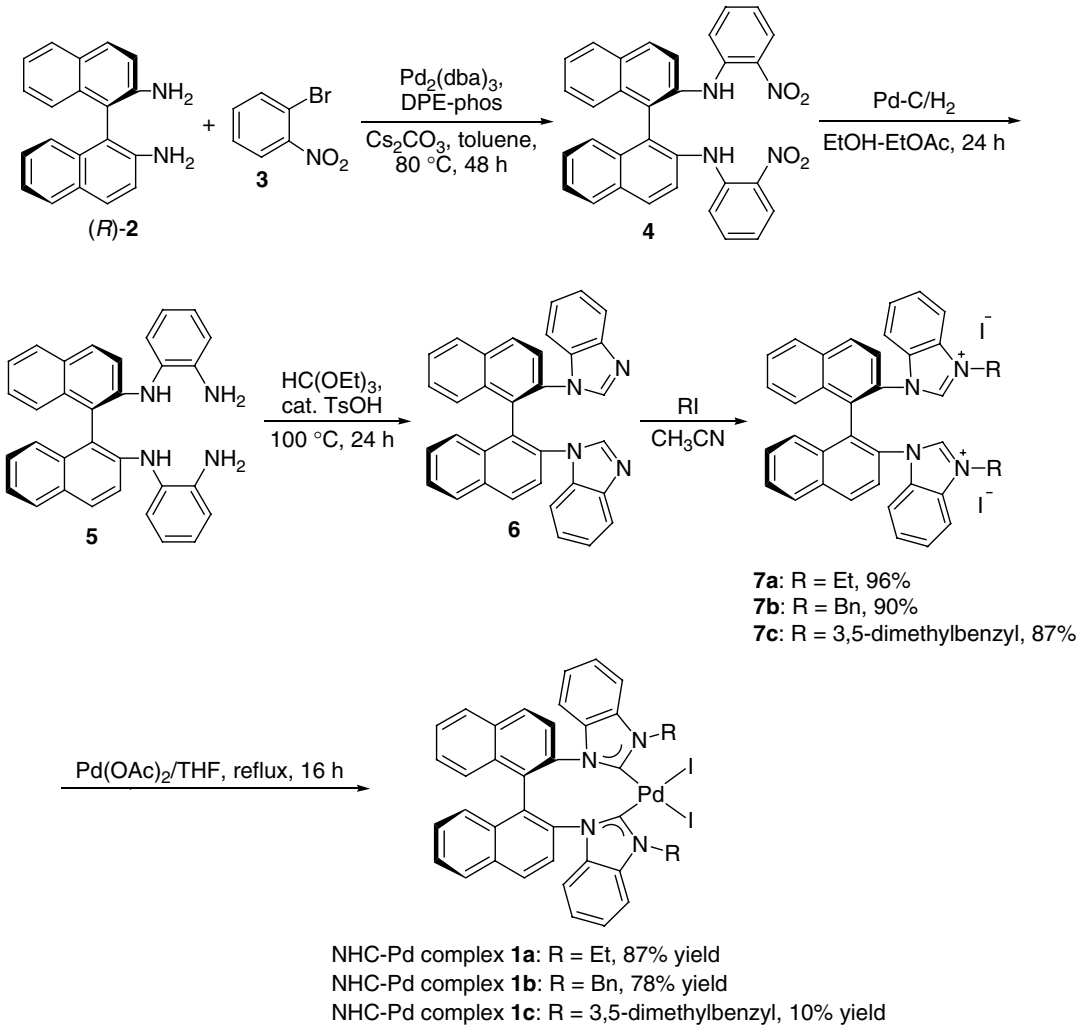
Selected bond distances (Å) and angles (deg) of (NHC)–Pd(II) complex **1a**

Bond distances	Bond angles
Pd–C(1) = 1.984(6)	C(1)–Pd–C(8) = 95.2(2)
Pd–C(8) = 2.004(5)	C(1)–Pd–I(1) = 88.16(17)
Pd–I(1) = 2.6645(6)	C(8)–Pd–I(1) = 163.58(16)
Pd–I(2) = 2.6704(6)	C(1)–Pd–I(2) = 160.57(16)
N(1)–C(1) = 1.376(7)	C(8)–Pd–I(2) = 89.31(15)
N(1)–C(2) = 1.394(7)	I(1)–Pd–I(2) = 92.81(2)
N(2)–C(1) = 1.339(7)	C(1)–N(1)–C(2) = 109.9(5)
N(2)–C(3) = 1.410(7)	C(1)–N(1)–C(35) = 125.5(5)
N(1)–C(35) = 1.467(8)	C(2)–N(1)–C(35) = 124.6(5)
N(2)–C(15) = 1.436(6)	C(1)–N(2)–C(15) = 123.3(5)

Selected bond distances (Å) and angles (deg) of (NHC)–Pd(II) complex **1b**

Bond distances	Bond angles
Pd–C(1) = 1.997(8)	C(1)–Pd–C(8) = 96.3(3)
Pd–C(8) = 2.008(7)	C(1)–Pd–I(1) = 93.2(2)
Pd–I(1) = 2.6828(8)	C(8)–Pd–I(1) = 157.9(2)
Pd–I(2) = 2.6667(8)	C(1)–Pd–I(2) = 161.1(2)
N(1)–C(1) = 1.353(9)	C(8)–Pd–I(2) = 84.5(2)
N(1)–C(3) = 1.412(9)	I(1)–Pd–I(2) = 92.79(3)
N(1)–C(35) = 1.448(9)	C(1)–N(1)–C(3) = 111.6(6)
N(2)–C(1) = 1.369(9)	C(1)–N(1)–C(35) = 128.6(6)
N(2)–C(2) = 1.406(9)	C(3)–N(1)–C(35) = 119.8(6)
N(2)–C(15) = 1.448(9)	C(1)–N(2)–C(15) = 128.3(6)

Applied Organometallic Chemistry



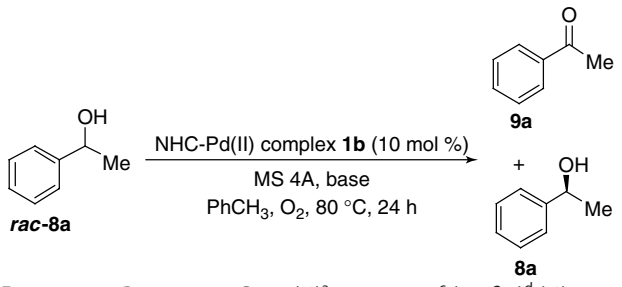
Scheme 1. Preparation of axially chiral NHC–Pd(II) complexes **1a–c**.

Next, the enantioselective oxidative kinetic resolution of 1-phenylethanol **8a** (racemate) was evaluated using chiral NHC–Pd(II) complex **1b** in the presence of various bases and solvents.[4b–f,8] The results of these experiments are summarized in Tables 1 and 2, respectively. It was found that PhMe was the solvent of choice (Tables 1 and 2, entries 1–4) and Cs_2CO_3 was the preferred base for the kinetic resolution, with this combination affording optically active 1-phenylethanol **8a** in 55% conv. and 55% ee at 80 °C (Table 1, entry 4). Other bases, such as Na_2CO_3, K_2CO_3, KO^{t}Bu and KOH, are not effective in this kinetic resolution to give optically active 1-phenylethanol **8a** in low conversions (Table 1, entries 2, 3, 9 and 14). Only in the presence of $K_3PO_4 \cdot 3H_2O$ was optically active 1-phenylethanol **8a** produced in 54% conv. and 43% ee (Table 1, entry 7).

With the optimized conditions in hand, we next investigated the substrate scope of this process in the presence of chiral NHC–Pd(II) complexes **1a** and **1b**. The results are summarized in Table 3. It can be seen from Table 3 that chiral NHC–Pd(II) complex **1a** is not as effective as **1b** in this kinetic resolution under the optimal conditions (Table 3, entry 1). Using chiral NHC–Pd(II) complex **1b** as the catalyst, a variety of substrates with an electron-withdrawing substituent or an electron-donating substituent on the aromatic ring provided the corresponding optically active secondary alcohols in better results, with 46–54% conversion, k_{rel} = 3.58–20.3 and 37–79% ee being observed (Table 3, entries 3–8).

Since the reaction outcomes were not satisfactory, we attempted to synthesize the axially chiral NHC–Pd(II) complex **1d** from (*R*)-H_8-BINAM, which has the similar structure to the axially chiral NHC–Pd(II) complex **B** (Fig. 1), to improve the efficiency in the oxidative kinetic resolution of secondary alcohols. The synthetic route is shown in Scheme 2 according to our previously reported procedure.[5] The corresponding axially chiral NHC–Pd(II) complex **1d** was obtained in 77% yield as a yellow solid. The results of oxidative kinetic resolution of secondary alcohols using NHC–Pd(II) complex **1d** as the catalyst are summarized in Table 4. It was found that the reaction outcomes could be improved significantly to give the corresponding secondary alcohols in higher ee's under oxygen atmosphere or aerobic conditions. For example, 1,2,3,4-tetrahydronaphthalen-1-ol gave promising resolution result, with selectivity factor 30.51 and 48.90 in the presence of complex **1d** under aerobic conditions and oxygen atmosphere, respectively (Table 4, entries 3 and 4). This is best result obtained for the oxidative kinetic resolution of secondary alcohols with chiral NHC–Pd(II) complex. As for phenyl-, naphthyl- and other naphthalen-1-ol derivatives, the corresponding secondary alco-

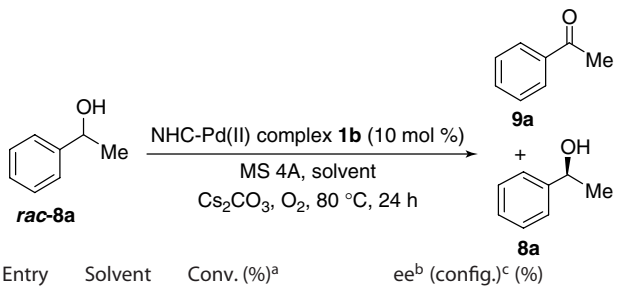
Table 1. Screening for bases



Entry	Base	Conv. (%)[a]	ee[c] (config.)[d] (%)
1[b]	/	N.R.[e]	–
2	Na_2CO_3	7	–
3	K_2CO_3	26	–
4	Cs_2CO_3	55	55 (*S*)
5	KF	4	–
6	NaOAc	4	–
7	$K_3PO_4 \cdot 3H_2O$	54	42 (*S*)
8	$NaHCO_3$	4	–
9	KO^tBu	17	–
10	DBU	14	–
11	DMAP	N.R.[e]	–
12	Et_3N	N.R.[e]	–
13	pyridine	4	–
14	KOH	17	–

[a] Conv. were analyzed by GC on the basis of the starting material and the formed ketone. [b] No base was added. [c] Measured by chiral HPLC. [d] Determined by comparison of the sign of the optical rotation to literature values. [e] N.R. = no reaction.

Table 2. Screening for solvents



Entry	Solvent	Conv. (%)[a]	ee[b] (config.)[c] (%)
1	CH_3CN	46	43 (*S*)
2	DMF	34	10 (*S*)
3	DCE	42	38 (*S*)
4	DMSO	9	–

[a] Conv. were analyzed by GC on the basis of the starting material and the formed ketone. [b] Measured by chiral HPLC. [c] Determined by comparison of the sign of the optical rotation to literature values.

hols were also obtained in moderate to good ee's, suggesting that chiral scaffold in NHC–Pd(II) complex plays an important role in the oxidative kinetic resolution of secondary alcohols, although they are not as efficient as complexes **A** and **B** (Table 4, entries 1–2 and 5–8).

In conclusion, we have designed and synthesized several novel axially chiral *N*-heterocyclic carbene (NHC) Pd(II) complexes **1a–1d** from optically active 1,1′-binaphthalenyl-2,2′-diamine (BINAM) and H_8-BINAM. Their crystal structures were been unambiguously determined by X-ray diffraction. We found that these *N*-heterocyclic carbene (NHC) Pd(II) complexes are fairly effective in the oxidative kinetic resolution of secondary alcohols using molecular oxygen as a terminal oxidant or under aerobic conditions, affording the corresponding *sec*-alcohols in good yields with moderate enantioselectivities, although they are not generally as good as NHC–Pd(II) complex **B**,[5] presumably because of the steric effect. Efforts are in progress to elucidate the mechanistic details of this reaction and to study its scope and limitations.

Experimental

General Remarks

Dichloromethane and 1,2-dichloroethane were freshly distilled from calcium hydride; THF and toluene were distilled from sodium (Na) under argon (Ar) atmosphere. Melting points were determined on a digital melting point apparatus and temperatures were uncorrected. Optical rotations were determined at 589 nm (sodium D line) by using a Perkin-Elmer-341 MC digital polarimeter; $[\alpha]_D$-values are given in unit of $10deg^{-1}$ cm^2 g^{-1}. ^1H NMR spectra were recorded on a Bruker AM-300 spectrometer for solution in $CDCl_3$ with tetramethylsilane (TMS) as an internal standard; coupling constants *J* are given in Hz. Infrared spectra were recorded on a Perkin-Elmer PE-983 spectrometer with absorption in cm^{-1}. Flash column chromatography was performed using 300–400 mesh silica gel. For thin-layer chromatography (TLC), silica gel plates (Huanghai GF_{254}) were used. Conversion was analyzed by GC using a supelcowax™-10 fused silica capillary column (30.0 m × 0.25 mm × 0.25 μm) purchased from Supelco Industries. Chiral HPLC was performed on a Shimadzu SPD-10A *vp* series with chiral columns [Chiralpak AS-H, OD-H and OJ-H columns 4.6 × 250 mm (Daicel Chemical Ind., Ltd)]. Elementary analysis was taken on a Carlo-Erba 1106 analyzer. Mass spectra were recorded by EI, and HRMS was measured on an HP-5989 instrument. Racemic alcohols were purchased from commercial company, prepared by corresponding aldehydes or reduced from corresponding ketones.

Axially chiral NHC–Pd(II) complexes **1a–d** were prepared by using similar procedures to those used for complexes **A** and **B**.[5]

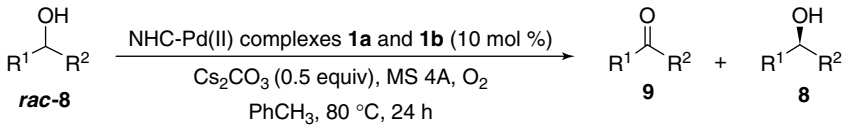
Compound ***4***[6]

A red solid; m.p. 202.8–203.3 °C; $[\alpha]^{20}_D$ −496.0 (*c* 0.22, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$, TMS): δ 6.58–6.64 (m, 2H, ArH), 7.10–7.23 (m, 6H, ArH), 7.32–7.36 (m, 2H, ArH), 7.46–7.52 (m, 2H, ArH), 7.69 (d, J = 8.7 Hz, 2H, ArH), 7.92–7.97 (m, 4H, ArH), 8.02 (d, J = 8.7 Hz, 2H, ArH), 9.03 (s, 2H, NH).

Compound ***5***[6]

A white solid; m.p. 257.2–258.4 °C; $[\alpha]^{20}_D$ +200.7 (*c* 0.39, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$, TMS): δ 4.37 (br, 4H, NH_2), 5.20 (br, 2H, NH), 6.75–6.80 (m, 4H, ArH), 7.00–7.08 (m, 4H, ArH), 7.15 (d, J = 9.0 Hz, 2H, ArH), 7.24–7.29 (m, 6H, ArH), 7.82–7.84 (m, 4H, ArH).

Table 3. Axially chiral NHC–Pd(II) complexes **1a** and **1b** catalyzed oxidative kinetic resolution of secondary alcohols[a]



Entry	Substrate	Pd(II)	R^1/R^2	Conv.[b] (%)	ee[c] (config.)[d] (%)	k_{rel}[e]
1	***rac*-8a**	**1a**	C_6H_4/Me	46	36 (*S*)	3.44
2	***rac*-8a**	**1b**	C_6H_4/Me	55	55 (*S*)	4.43
3	***rac*-8b**	**1b**	*p*-ClC_6H_4/Me	50	43 (*S*)	3.74
4	***rac*-8c**	**1b**	*p*-BrC_6H_4/Me	46	37 (*S*)	3.58
5	***rac*-8d**	**1b**	*p*-MeC_6H_4/Me	52	51 (S)	4.50
6	***rac*-8e**	**1b**	*p*-$MeOC_6H_4$/Me	46	48 (*S*)	5.67
7	***rac*-8f**	**1b**	1-naphthyl/Me	54	53 (*S*)	4.36
8	***rac*-8g**	**1b**		50	79 (*S*)	20.3

[a] 1.0 atm of O_2, 0.1 M substrate concentration in PhMe. [b] Analyzed by GC on the basis of the starting material and the formed ketone. [c] Measured by chiral HPLC. [d] Determined by comparison of the sign of the optical rotation to literature values. [e] $k_{rel} = \ln[(1 - C)(1 - ee)]/\ln[(1 - C)(1 + ee)]$.

Compound ***6***[6]

A white solid; m.p. 294.5–294.8 °C; $[\alpha]^{20}_D$ +516.7 (*c* 0.97, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 6.12 (d, 2H, $J = 8.7$ Hz, ArH), 6.51 (t, 2H, $J = 7.5$ Hz, ArH), 6.94–6.97 (m, 2H, ArH), 7.00 (s, 2H, CH), 7.45 (d, $J = 8.7$ Hz, 2H, ArH), 7.49–7.58 (m, 6H, ArH), 7.65–7.70 (m, 2H, ArH), 8.08 (d, $J = 8.7$ Hz, 4H, ArH).

Synthesis of compounds ***7a–c***

Compound **6** (99 mg, 0.20 mmol) and RI (0.5 mmol) in CH_3CN (4.0 ml) were stirred under reflux for 5 h. After cooling to room temperature, volatiles were removed under reduced pressure and the obtained solid compound was used for the next reaction without further purification.

Compound ***7a***

A pale yellow solid; m.p. > 250 °C (dec.); $[\alpha]^{20}_D$ +32.8 (*c* 0.550, $CHCl_3$); IR (CH_2Cl_2) ν 2978, 2924, 1738, 1555, 1365, 1228, 941, 820 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 1.03–1.12 (m, 6H, CH_3), 4.44–4.47 (m, 4H, CH_2), 6.99 (d, $J = 8.4$ Hz, 2H, ArH), 7.49–7.83 (m, 12H, ArH), 7.80–8.12 (m, 4H, ArH), 8.32–8.34 (m, 2H, ArH); MS (ESI) *m/e*: 671.1 ($M^+ - I$), 272.1 ($M^+ - 2I$)/2.

Compound ***7b***

A pale yellow solid; m.p. > 250 °C (dec.); $[\alpha]^{20}_D$ +61.5 (*c* 0.565, $CHCl_3$); IR (CH_2Cl_2) ν 3012, 2956, 2927, 1602, 1551, 1508, 1455, 1261, 824 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 5.55 (d, $J = 9.6$ Hz, 2H, $ArCH_2$), 5.65 (d, $J = 8.1$ Hz, 2H, $ArCH_2$), 6.67–6.71 (m, 2H, ArH), 6.97–7.01 (m, 4H, ArH), 7.18–7.41 (m, 16H, ArH), 7.58–7.78 (m, 4H, ArH), 8.12–8.49 (m, 4H, ArH), MS (ESI) *m/e*: 795.0 ($M^+ - I$), 334.1 ($M^+ - 2I$)/2.

Compound ***7c***

A pale yellow solid; m.p. > 250 °C (dec.); $[\alpha]^{20}_D$ + 119.1 (*c* 0.505, $CHCl_3$); IR (CH_2Cl_2) ν 3013, 2924, 2850, 1709, 1610, 1552, 1486, 1363, 1221, 823 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 2.30 (s, CH_3, 12H), 5.37 (s, 2H, $ArCH_2$), 6.05 (s, $ArCH_2$), 6.39–7.03 (m, 8H, ArH), 7.49–7.83 (m, 14H, ArH), 8.01–8.33 (m, 4H, ArH), MS (ESI) *m/e*: 851.3 ($M^+ - I$, 20), 605.3 (100), 362.2 (56).

NHC–Pd(II) complex ***1a***

A yellow solid; m.p. > 250 °C (dec.); $[\alpha]^{20}_D$ +192.9 (*c* 0.540, $CHCl_3$); IR (CH_2Cl_2) ν 3056, 2930, 2857, 1470, 1389, 1344, 1267, 832 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 1.17–1.26 (m, 6H, CH_3), 3.88–4.06 (m, 2H, CH_2), 5.22–5.49 (m, 2H, CH_2), 6.67 (d, $J = 8.4$ Hz, 2H, ArH), 6.79–6.98 (m, 8H, ArH), 7.13–7.32 (m, 4H, ArH), 7.54–7.75 (m, 2H, ArH), 7.87–7.80 (m, 4H, ArH); MS (ESI) *m/e* 687.1 ($M^+ - 2I + K$, 100), 779.0 ($M^+ - I$, 59). Anal. calcd for $C_{38}H_{30}I_2N_4Pd$: C: 50.55, H: 3.35, N, 6.21%. Found: C: 50.90, H: 3.86, N, 5.65%.

NHC–Pd(II) complex ***1b***

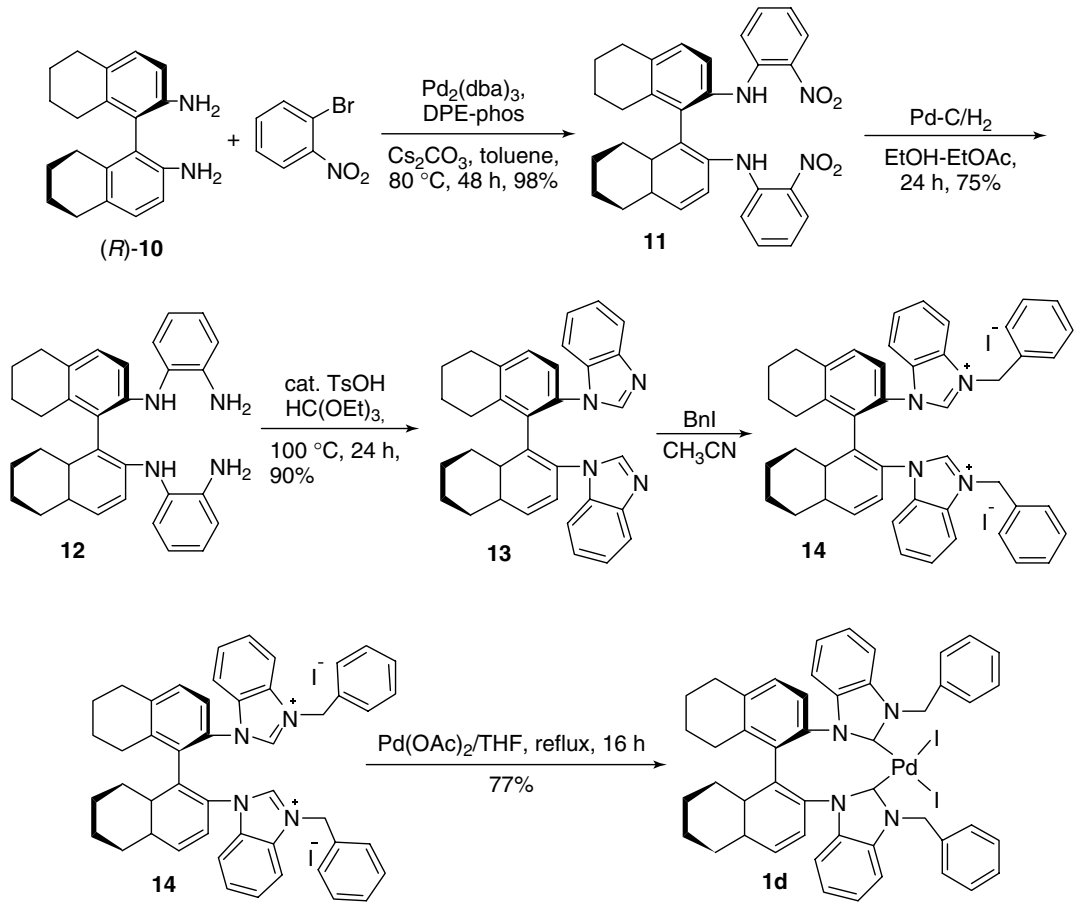
A yellow solid; m.p. > 250 °C (dec.); $[\alpha]^{20}_D$ +166.0 (*c* 0.285, $CHCl_3$); IR (CH_2Cl_2) ν 3060, 2954, 2925, 2847, 1474, 1389, 1335, 1296, 823 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 5.37 (d, $J = 15.6$ Hz, 2H, $ArCH_2$), 6.37 (d, $J = 15.6$ Hz, 2H, $ArCH_2$), 6.78–6.82 (m, 4H, ArH), 6.89–6.95 (m, 8H, ArH), 7.00–7.05 (m, 4H, ArH), 7.22–7.27 (m, 6H, ArH), 7.31–7.36 (m, 2H, ArH), 7.66 (d, $J = 8.1$ Hz, 2H, ArH), 7.79–7.88 (m, 4H, ArH), HRMS calcd for $C_{48}H_{34}I_2N_4Pd$ requires 1022.9837. Found: 1022.9835. Anal. calcd for $C_{48}H_{34}I_2N_4Pd$: C: 56.13, H: 3.34, N, 5.46%. Found: C: 55.87, H: 3.30, N, 5.12%.

NHC–Pd(II) complex ***1c***

A yellow solid; m.p. > 250 °C (dec.); IR (CH_2Cl_2) ν 3056, 2924, 2854, 1715, 1507, 1473, 1393, 1239, 817 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ 2.22 (s, CH_3), 4.07 (d, $J = 15.9$ Hz, 2H, $ArCH_2$), 6.39 (d, $J = 11.7$ Hz, 2H, $ArCH_2$), 6.70–7.00 (m, 6H, ArH), 7.27–7.38 (m, 4H, ArH), 7.48–7.59 (m, 4H, ArH), 7.69–7.70 (m, 4H, ArH), 7.91–8.01 (m, 6H, ArH), MS (ESI) *m/e* 955.1 ($M^+ - I$, 100).

Compounds ***11, 12*** *and* ***13***

These are known products and their spectroscopic data are consistent with those reported.[5]



Scheme 2. Preparation of axially chiral NHC–Pd(II) complex **1d**.

*Compound **14***

A pale yellow solid; m.p. $>$ 250 °C (dec.); $[\alpha]^{20}_D$ +53 (*c* 0.50, $CHCl_3$); IR (CH_2Cl_2) ν 3024, 2935, 2861, 1548, 1486, 1467, 1408, 1263, 1082, 839 cm^{-1}; MS (ESI) *m/e*: 585.2 ($M^+ - 2I - Bn$), 338.1 ($M^+ - 2I$)/2.

*NHC–Pd(II) complex **1d***

A yellow solid; m.p. $>$ 250 °C (dec.); $[\alpha]^{20}_D$ +83 (*c* 0.245, $CHCl_3$); IR (CH_2Cl_2) ν 3058, 2928, 2857, 1716, 1478, 1378, 1342, 1251, 832 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$, TMS): δ 1.26–1.33 (8H, m, CH_2), 1.43–1.49 (2H, m, CH_2), 1.76–1.89 (2H, m, CH_2), 2.38–2.42 (2H, m, CH_2), 2.62–2.66 (2H, m, CH_2), 5.29 (2H, s, $ArCH_2$), 6.60–6.64 (2H, m, ArH), 6.85–6.91 (4H, m, ArH), 7.02–7.14 (8H, m, ArH), 7.24–7.34 (8H, m, ArH); MS (ESI) *m/e* (%): 179.02 (M^+, 18), 330.34 (M^+, 12), 907.15 (M^+, 100), 1033.04 (M^+, 25). HRMS (Micromass LCT) calcd for $C_{48}H_{42}I_2N_4Pd$: 1034.0534; Found: 1035.0410.

General Procedure for the Oxidation of Secondary Alcohols

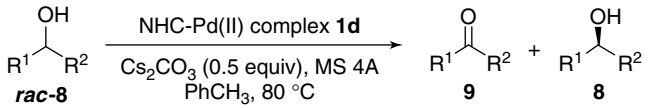
Base screening trials

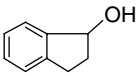
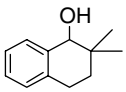
A 25 ml Schlenk flask equipped with a magnetic stir bar was charged with powdered molecular sieves (MS 4 Å, 250 mg) and flame-dried under vacuum. After cooling under dry Ar, chiral NHC–Pd(II) complex **1b** (26 mg, 0.025 mmol, 0.05 equiv.), and base (0.25 mmol, 0.5 equiv.) was added followed by toluene (5.0 ml). The flask was vacuum evacuated and filled with O2 (three times, balloon), and then the alcohol (0.50 mmol, 1.0 equiv.) was introduced. The reaction mixture was allowed stirred at 80 °C for 24 h. After cooling to room temperature, the reaction mixture was filtered through a small plug of silica gel (eluent: ethyl acetate), and biphenyl (38.5 mg, 0.25 mmol, 0.5 equiv.) was added as internal standard, then analyzed by GC for percentage conversion. After that, the solvent was removed under reduced pressure and the residue was purified by a silica gel flash column chromatography (eluent: petroleum ether–ethyl acetate, 15 : 1 to 10 : 1) to give 1-phenylethanol as a colorless oil, which was analyzed by HPLC for enantiomeric excess.

Solvent Screening Trials

A 25 ml Schlenk flask equipped with a magnetic stir bar was charged with powdered molecular sieves (MS 4 Å, 250 mg) and flame-dried under vacuum. After cooling under dry Ar, chiral NHC–Pd(II) complex **1b** (26 mg, 0.025 mmol, 0.05 equiv.), and Cs_2CO_3 (81.5 mg, 0.25 mmol, 0.5 equiv.) were added followed by solvent (5.0 ml). The flask was vacuum evacuated and filled with O_2 (three times, balloon), then the alcohol (0.50 mmol, 1.0 equiv.) was introduced. The reaction mixture was stirred at 80 °C for 24 h. After cooling to room temperature, the reaction mixture was filtered through a small plug of silica gel (eluent: ethyl acetate), and biphenyl (38.5 mg, 0.25 mmol, 0.5 equiv.) was added as internal standard, then analyzed by GC for percentage conversion. After that, the solvent was removed under reduced pressure and the residue was purified by a silica gel flash column chromatography (eluent: petroleum ether–ethyl acetate, 15 : 1 to 10 : 1) to give

Table 4. Axially chiral NHC–Pd(II) complex **1d** catalyzed oxidative kinetic resolution of secondary alcohols under oxygen atmosphere or aerobic condition



Entry[a]	Substrate	R^1/R^2	Cat. **1d** (mol%)	Conv.[b] (%)	ee[c] (config.)[d] (%)	k_{rel}[e]	Time (h)
1[f]	***rac*-8c**	*p*-BrC_6H_4/Me	15	54	62 (*S*)	5.93	24
2[g]	***rac*-8c**	*p*-BrC_6H_4/Me	10	61	72 (*S*)	5.55	24
3[f]	***rac*-8g**		15	58	>99 (*S*)	30.51	12
4[g]	***rac*-8g**		10	55	>99 (*S*)	48.96	24
5[f]	***rac*-8f**	2-naphthyl/Me	15	50	56 (*S*)	6.09	24
6[g]	***rac*-8f**	2-naphthyl/Me	10	60	60 (*S*)	4.11	24
7[f]	***rac*-8h**		15	69	73 (*S*)	3.98	30
8[f]	***rac*-8i**		15	49	69 (*S*)	12.41	72

[a] 0.1 M substrate concentration in PhMe. [b] Analyzed by GC. [c] Measured by chiral HPLC. [d] Determined by comparison of the sign of optical rotation to literature values. [e] $k_{rel} = \ln[(1 - C)(1 - ee)]/\ln[(1 - C)(1 + ee)]$. [f] Under air atmosphere. [g] Under oxygen atmosphere.

1-phenylethanol as a colorless oil, which was analyzed by HPLC for enantiomeric excess. *During examination of the solvent effects under oxygen atmosphere, the reaction should be carried out with caution at elevated temperature.*

General Procedure for the Oxidative Kinetic Resolution of Secondary Alcohols

A 25 ml Schlenk flask equipped with a magnetic stir bar was charged with powdered molecular sieves (MS 4 Å, 250 mg) and flame-dried under vacuum. After cooling under dry Ar, chiral NHC–Pd(II) complex **1b** (53 mg, 0.05 mmol, 0.1 equiv.) and Cs_2CO_3 (81.5 mg, 0.25 mmol, 0.5 equiv.) were added followed by toluene (3.0 ml). The flask was vacuum evacuated and filled with O_2 (three times, balloon), and then the alcohol (0.50 mmol, 1.0 equiv.) was introduced. The reaction mixture was allowed stirred at 80 °C for 24 h. After cooling to room temperature, the reaction mixture was filtered through a small plug of silica gel (eluent: ethyl acetate), then analyzed by GC for percentage conversion. After that, the solvent was removed under reduced pressure and the residue was purified by a silica gel flash column chromatography (eluent: petroleum ether–ethyl acetate, 15 : 1 to 10 : 1) to give 1-phenylethanol as a colorless oil, which was analyzed by HPLC for enantiomeric excess.

Supporting information

Supporting information of the spectroscopic and analytical data for the compounds shown in Tables 1, 2 and 3 and the detailed description of experimental procedures are included in supporting information for this article, which is available on online version of this article or from the author.

Supporting information may be found in the online version of this article.

Acknowledgements

We thank the Shanghai Municipal Committee of Science and Technology (06XD14005, 08dj1400100-2), National Basic Research Program of China (973)-2009CB825300, and the National Natural Science Foundation of China for financial support (20872162, 20672127, and 20732008).

References

[1] For reviews, see: a) W. A. Herrmann, *Angew. Chem., Int. Ed.* **2002**, *41*, 1209; b) V. César, S. Bellemin-Laponnaz, L. H. Gade, *Chem. Soc. Rev.* **2004**, *33*, 619; c) F. Ekkehardt Hahn, M. C. Jahnke, *Angew. Chem. Int. Ed.* **2008**, *47*, 3122; d) E. A. B. Kantchev, C. J. O'Brien, M. G. Organ, *Angew. Chem. Int. Ed.* **2007**, *46*, 2768; e) C. M. Crudden, D. P. Allen, *Coord. Chem. Rev.* **2004**, *248*, 2247; f) S. P. Nolan (Ed.), *N-Heterocyclic Carbenes in Synthesis*. Wiley-VCH: Weinheim, **2006**; g) F. A. Glorius, *Top. Organomet. Chem.* **2007**, *21*, 1.

[2] Selected examples, see: a) R. A. Batey, M. Shen, A. J. Lough, *Org. Lett.* **2002**, *4*, 1411; b) O. Navarro, H. Kaur, P. Mahjoor, S. P. Nolan, *J. Org. Chem.* **2004**, *69*, 3173; c) Q. Xu, W. L. Duan, Z. Y. Lei, Z. B. Zhu, M. Shi, *Tetrahedron* **2005**, *61*, 11225; d) N. Marion, O. Navarro, J. Mei, E. D. Stevens, N. M. Scott, S. P. Nolan, *J. Am. Chem. Soc.* **2006**, *128*, 4101.

[3] a) T. Zhang, M. Shi, *Chem. Eur. J.* **2008**, *14*, 3759; b) L. G. Bonnet, R. E. Douthwaite, B. M. Kariuki, *Organometallics* **2003**, *22*, 4187; c) A. Flahaut, J.-P. Baltaze, S. Roland, P. Mangeney, *J. Organomet. Chem.* **2006**, *691*, 3498.

[4] a) D. R. Jensen, M. S. Sigman, *Org. Lett.* **2003**, *5*, 63; For recent reviews, see b) J. Muzart, *Tetrahedron* **2003**, *59*, 5789; c) S. S. Stahl, *Angew. Chem., Int. Ed.* **2004**, *43*, 3400; d) M. J. Schultz, M. S. Sigman, *Tetrahedron* **2006**, *62*, 8227; e) M. S. Sigman, D. R. Jensen, *Acc. Chem. Res.* **2006**, *39*, 221; f) M. M. Rogers, S. S. Stahl, in *N-Heterocyclic Carbenes in Transition Metal Catalysis* (Ed.: Glorius, F). Springer: New York, **2007**, Vol. 21, pp. 21.

[5] T. Chen, J.-J. Jiang, Q. Xu, M. Shi, *Org. Lett.* **2007**, *9*, 865.

[6] W.-L. Duan, M. Shi, G.-B. Rong, *Chem. Commun.* **2003**, 2916.

[7] a) M. Shi, H. X. Qian, *Appl. Organoment. Chem.* **2005**, *19*, 1083; b) M. Shi, H. X. Qian, *Tetrahedron* **2005**, *61*, 4949.
[8] For some more selected examples, see: a) K. P. Peterson, R. C. Larock, *J. Org. Chem.* **1998**, *63*, 3185; b) T. Nishimura, T. Onoue, K. Ohe, S. Uemura, *J. Org. Chem.* **1999**, *64*, 6750; c) G.-J. Brink, I. W. C. E. Arends, R. A. Sheldon, *Science* **2000**, *287*, 1636; d) B. A. Steinhoff, S. S. Stahl, *Org. Lett.* **2002**, *4*, 4179; e) M. J. Schultz, C. C. Park, M. S. Sigman, *Chem. Commun.* **2002**, 3034; f) D. R. Jensen, M. J. Schultz, J. A. Mueller, M. S. Sigman, *Angew. Chem., Int. Ed.* **2003**, *42*, 3810; g) M. J. Schultz, S. S. Hamilton, D. R. Jensen, M. S. Sigman, *J. Org. Chem.* **2005**, *70*, 3343; h) D. R. Jensen, J. S. Pugsley, M. S. Sigman, *J. Am. Chem. Soc.* **2001**, *123*, 7475; i) J. A. Mueller, D. R. Jensen, M. S. Sigman, *J. Am. Chem. Soc.* **2002**, *124*, 8202; j) E. M. Ferreira, B. M. Stoltz, *J. Am. Chem. Soc.* **2001**, *123*, 7725; k) J. T. Bagdanoff, E. M. Ferreira, B. M. Stoltz, *Org. Lett.* **2003**, *5*, 835.

