JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
pubs.acs.org/JACS

Chiral Dienes as "Ligands" for Borane-Catalyzed Metal-Free Asymmetric Hydrogenation of Imines

Yongbing Liu and Haifeng Du*

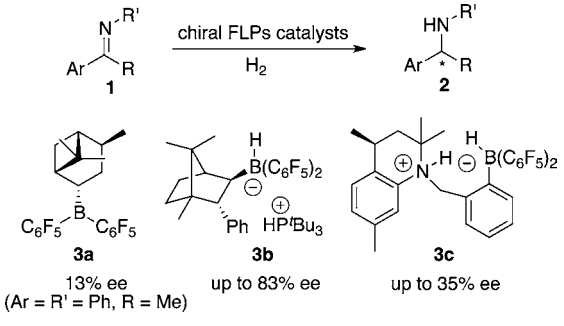
Beijing National Laboratory for Molecular Sciences, CAS Key Laboratory of Molecular Recognition and Function, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China

Supporting Information

ABSTRACT: This paper describes a highly enantioselective metal-free hydrogenation of imines using chiral dienes as "ligands" for the generation of catalysts with $HB(C_6F_5)_2$ by hydroboration *in situ* to furnish a variety of chiral amines with up to 89% ee, which provides a practical strategy for the development of novel chiral frustrated Lewis pairs for asymmetric hydrogenation.

Since Stephan and co-workers accomplished the first metal-free reversible hydrogen activation by an intramolecular combination of strong Lewis acid and base in 2006,[1] the area of frustrated Lewis pairs (FLPs) has witnessed an extremely rapid growth, and FLPs have become one promising catalyst class for homogeneous hydrogenation, which has been predominated by transition-metal catalysis.[2,3] Over the past 5 years, FLP-catalyzed metal-free hydrogenation of imines,[4] *N*-heterocycles,[2e,5] nitriles,[4a,c] alkenes,[4b,e,j,l,6] and so on[7] has been successfully realized. In particular, important progress has been achieved in the challenging field of asymmetric hydrogenation promoted by FLPs. In 2008, Klankermayer and co-workers reported the first FLP-catalyzed asymmetric hydrogenation of an imine using α-pinene-derived chiral borane **3a** to furnish the desired chiral amine with 13% ee (Scheme 1).[4d]

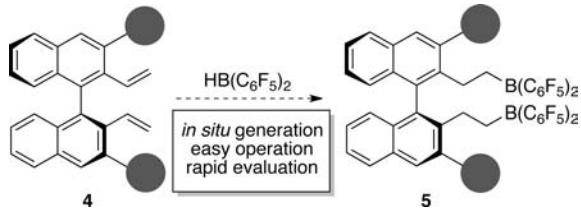
Scheme 1. Seminal Work on Chiral FLP-Catalyzed Asymmetric Hydrogenation of Imines



Subsequently, the same group reported the first example of highly enantioselective hydrogenation with chiral FLP salts **3b** generated by treating (+)-camphor-derived chiral borane and tri-*tert*-butylphosphine with H_2 (Scheme 1).[8a,b] Very recently, Repo and co-workers reported the use of chiral *ansa*-ammonium borate **3c** for the asymmetric hydrogenation of imines and 2-phenylquinoline with up to 37% ee (Scheme 1).[8c] Moreover, Stephan and co-workers described a diastereoselective catalytic hydrogenation of chiral imines using $B(C_6F_5)_3$.[8d] Despite the aforementioned progress, highly enantioselective metal-free hydrogenation promoted by chiral FLPs still remains a formidable challenge, and the development of highly efficient and readily accessible chiral FLP catalysts is one of the most important subjects in this area.

As a recently emerging ligand class, chiral olefins have been widely utilized as steering ligands for transition-metal-catalyzed asymmetric reactions.[9] In comparison with a variety of well-established chiral diene ligands containing internal olefins and rigidly bicyclic frameworks,[10] several flexible acyclic diene ligands bearing two terminal olefins have also been successfully developed by our group[11] and those of Yu[12a] and Trost.[12b] Inspired by early work on the synthesis of intramolecular FLPs from vinyldimesitylphosphane by Erker's group[13] and the seminal work on asymmetric hydrogenation with chiral borane by Klankermayer's group,[4d] we envision that direct hydroboration of chiral dienes bearing two terminal olefins with $HB(C_6F_5)_2$[14] probably provides an excellent opportunity to access simple chiral borane catalysts for metal-free hydrogenation of imines (Scheme 2).[15] In this strategy, binaphthyl-

Scheme 2. Our Strategy for the Development of Novel Catalysts from Chiral Dienes



based chiral diene **4** acts like a "ligand" in the transition-metal catalysis to generate the borane catalyst **5** *in situ* without further isolation, which ensures easy operation and rapid evaluation. Moreover, terminal olefins will generate enantiomerically pure boranes by hydroboration with $HB(C_6F_5)_2$ instead of the diastereoisomer mixture in the case of internal olefins. Herein, we report our preliminary results on this subject.

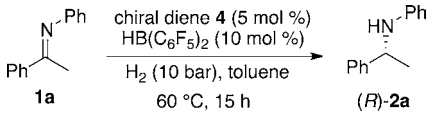
The feasibility of our strategy for metal-free asymmetric hydrogenation was initially examined using imine **1a** as substrate under H_2 (10 bar) with a chiral borane catalyst

Received: March 13, 2013
Published: April 22, 2013

   dx.doi.org/10.1021/ja4025808 | *J. Am. Chem. Soc.* 2013, 135, 6810−6813

generated *in situ* from $HB(C_6F_5)_2$ (10 mol%) and chiral diene **4a** (5 mol%) in toluene at 60 °C for 15 h. We were pleased to find that this reaction went cleanly to give chiral amine **2a** with 20% ee (Table 1, entry 1). Although the enantioselectivity is

Table 1. Evaluation of Chiral Dienes for Asymmetric Hydrogenation of Imine 1a[a,b]



entry	diene	conv (%)[c]	ee (%)[d]	entry	diene	conv (%)[c]	ee (%)[d]
1	**4a**	100	20	9	**4i**	100	25
2	**4b**	100	16	10	**4j**	100	25
3	**4c**	100	8	11	**4k**	100	30
4	**4d**	100	17	12	**4l**	100	40
5	**4e**	100	14	13	**4m**	100	31
6	**4f**	100	22	14	**4n**	100	60
7	**4g**	100	26	15	**4o**	100	50
8	**4h**	100	12	16	**4p**	100	41

[a]All reactions were carried out with imine **1a** (0.25 mmol), $HB(C_6F_5)_2$ (10 mol%), chiral diene (5 mol%), and H_2 (10 bar) in toluene (2.0 mL) at 60 °C for 15 h. [b]The absolute configuration of **2a** was assigned by comparing the optical rotation with the reported value. [c]The conversion was determined by crude ^1H NMR. [d]The ee was determined by chiral HPLC (Chiralcel OD-H column).

not satisfactory, this interesting result prompted us to further explore more effective chiral diene "ligands" by tuning the substituents at the 3,3′-positions of binaphthyl frameworks. As shown in Figure 1, chiral dienes **4b**–**o** bearing a wide range of

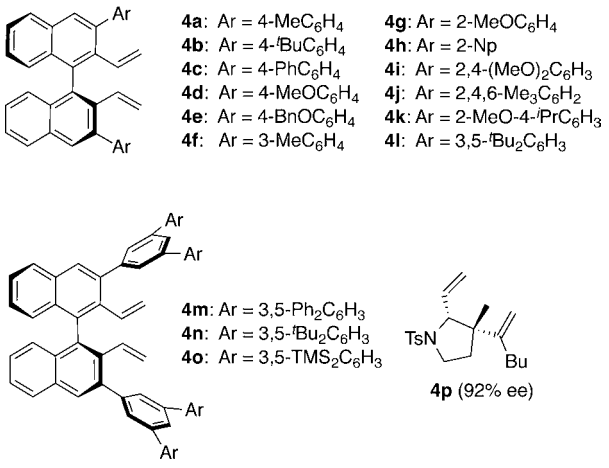


Figure 1. Representative chiral diene "ligands" for FLP-catalyzed asymmetric hydrogenation of imines.

aryl substituents were therefore prepared and evaluated. It was found that the steric bulkiness of the aryl substituent has a large impact on enantioselectivity, although all these dienes can lead a quantitative conversion of imine **1a** (Table 1, entries 2–15). Chiral diene **4n** proved to be the optimal "ligand" to give the desired amine **2a** with 60% ee (Table 1, entry 15). Moreover, a promising result (100% conversion, 41% ee) was also obtained with chiral diene **4p** developed by Yu's group,[12a] which provides additional opportunities for further improvement (Table 1, entry 16).

Encouraged by the results obtained with chiral diene **4n**, we subsequently investigated reaction conditions including solvents, temperature, and catalyst loading to further improve the enantioselectivity. Some of the results are summarized in Table 2. Solvents were found to have a large impact on both reactivity

Table 2. Optimization of Reaction Conditions for Asymmetric Hydrogenation of Imine 1a[a]

entry	solvent	temp (°C)	conv (%)[b]	ee (%)[c]
1	toluene	30	100	66
2	benzene	30	100	61
3	mesitylene	30	100	72
4	hexane	30	100	55
5	CH_2Cl_2	30	14	43
6	Et_2O	30	trace	–
7	^{t}BuOMe	30	72	6
8	PhOMe	30	78	66
9	mesitylene	rt	100	75
10	mesitylene	0	100	75
11[d]	mesitylene	rt	100	77
12[e]	mesitylene	rt	100	78

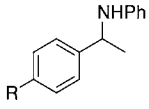
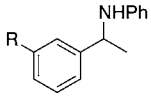
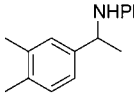
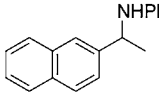
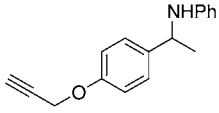
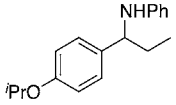
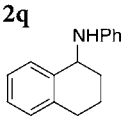
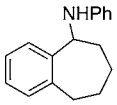
[a]All reactions were carried out with imine **1a** (0.25 mmol), $HB(C_6F_5)_2$ (10 mol%), chiral diene **4n** (5 mol%), and H_2 (20 bar) in solvent (2.0 mL) for 15 h unless otherwise noted. [b]The conversion was determined by crude ^1H NMR. [c]The ee was determined by chiral HPLC (Chiralcel OD-H column). [d]Imine **1a** (0.5 mmol), $HB(C_6F_5)_2$ (5 mol %), and diene **4n** (2.5 mol%) were used. [e]Imine **1a** (0.5 mmol), $HB(C_6F_5)_2$ (2.5 mol%), and diene **4n** (1.25 mol%) were used.

and enantioselectivity (Table 2, entries 1–8). Mesitylene proved to be a suitable solvent to give 72% ee (Table 2, entry 3). Lowering the temperature from 30 to 0 °C led to only a slightly higher ee (Table 2, entry 3 vs 10). Significantly, reducing the diene loading from 5 to 1.25 mol% gave a better ee without loss of any activity (Table 2, entry 9 vs 12).

With the optimal chiral diene and reaction conditions in hand, metal-free asymmetric hydrogenations of various imines were next studied. As shown in Table 3, a variety of imines can be smoothly hydrogenated in good yields and high enantioselectivities (74–89% ee). Both electron-donating and -withdrawing substituents at the *para*-positon of phenyl group were well tolerated for this reaction (Table 3, entries 2–10). *Meta*-substituted imines were also suitable substrates to give 74–80% ee (Table 3, entries 11–15). However, *ortho*-substituted imines still cannot give satisfactory results under the current conditions.[16] It is noteworthy that the alkyne group was also tolerated for this asymmetric catalytic system to give chiral amine **2p** in 95% yield with 85% ee (Table 3, entry 16). When the imine derived from 4-isopropoxyphenyl-propanone was used as substrate, the asymmetric hydrogenation went cleanly to afford product **2q** with 78% ee (Table 3, entry 17). The substrate scope can also been successfully extended to imines derived from cyclic ketones (Table 3, entries 18 and 19). Unfortunately, for the challenging diaryl or dialkyl ketimine substrates in transition-metal-catalyzed asymmetric hydrogenation,[15] the chiral borane catalyst exhibited high activity but poor enantioselectivity (<20% ee) (see Supporting Information). Although further improvement is still necessary, to the best of our knowledge, the current system gives the highest enantioselectivity (89% ee) in the field of FLP-catalyzed asymmetric hydrogenation to date.[8]

dx.doi.org/10.1021/ja4025808 | J. Am. Chem. Soc. 2013, 135, 6810–6813

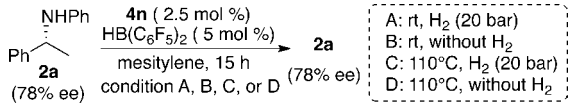
Table 3. Asymmetric Hydrogenation of Imines[a]

entry	product (**2**)	yield (%)[e]	ee (%)[f]
			
1[b,c]	**2a**: R = H	98	78
2	**2b**: R = Et	99	84
3	**2c**: R = ^{t}Bu	97	85
4	**2d**: R = Ph	97	82
5[c]	**2e**: R = MeO	99	84
6	**2f**: R = EtO	97	86
7	**2g**: R = ^{i}PrO	98	88
8[d]	**2h**: R = BnO	91	89
9	**2i**: R = CF_3O	96	88
10[c]	**2j**: R = CF_3	97	85
			
11[d]	**2k**: R = Me	92	78
12[d]	**2l**: R = MeO	91	80
13	**2m**: R = Cl	97	79
14	 **2n**	99	79
15[c]	 **2o**	94	74
16	 **2p**	95	85
17[d]	 **2q**	93	78
18	 **2r**	96	79
19	 **2s**	63	88

[a]All reactions were carried out with imine (0.5 mmol), $HB(C_6F_5)_2$ (5 mol%), diene **4n** (2.5 mol%), and H_2 (20 bar) in mesitylene (2.0 mL) at room temperature for 15 h unless otherwise noted. [b]$HB(C_6F_5)_2$ (2.5 mol%) and diene **4n** (1.25 mol%) were used. [c]The absolute configuration is *R*. [d]Imine (0.25 mmol), $HB(C_6F_5)_2$ (10 mol%), and diene **4n** (5 mol%) were used. [e]Isolated yield. [f]The ee was determined by chiral HPLC.

An NMR study indicates that the desired chiral borane is generated cleanly by mixing chiral diene **4n** and $HB(C_6F_5)_2$ in C_6D_6 at room temperature for several minutes (see Supporting Information). A complete racemization of chiral amines in the presence of $B(C_6F_5)_3$ was reported to occur at high temperature;[8c] therefore, the impact of chiral boranes on the enantioenriched amine **2a** was investigated. As shown in Scheme 3, the ee value of amine **2a** is well maintained after its

Scheme 3. Impact of Chiral Borane on Enantioenriched Amine



treatment with chiral boranes at room or high temperature under or without H_2, which demonstrates that there is no racemization involved in this catalytic system.

In summary, a highly enantioselective metal-free hydrogenation of imines using simple chiral borane (1.25−5 mol%) as catalyst, generated *in situ* from readily available chiral dienes and $HB(C_6F_5)_2$ under mild conditions, has been successfully achieved to furnish a variety of chiral amines in 63−99% yield with 74−89% ee. In this study, chiral diene is utilized like a chiral "ligand" in the transition-metal catalysis, which provides an alternative and practical strategy for the development of accessible and highly efficient chiral FLP catalysts for the metal-free asymmetric catalysis. Further understanding the asymmetric induction of chiral borane catalysts, developing a more effective asymmetric hydrogenation process using different types of chiral olefins, and expanding the substrate scope are under investigation in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information

Procedure for the metal-free catalytic asymmetric hydrogenation of imines and chiral diene synthesis; characterization of dienes, imines, and products; and data for the determination of enantiomeric excesses. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

haifengdu@iccas.ac.cn

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful for generous financial support from the National Natural Science Foundation of China (20802079, 21222207) and the National Basic Research Program of China (973 program, 2011CB808600). We also thank Prof. Zhi-Xiang Yu from Perking University for a gift of chiral diene **4p**.

■ REFERENCES

(1) Welch, G. C.; Juan, R. R. S.; Masuda, J. D.; Stephan, D. W. *Science* **2006**, *314*, 1124−1126.

(2) For selected reviews on frustrated Lewis pairs, see: (a) Stephan, D. W. *Org. Biomol. Chem.* **2008**, *6*, 1535−1539. (b) Stephan, D. W. *Dalton Trans.* **2009**, 3129−3136. (c) Stephan, D. W.; Erker, G. *Angew. Chem., Int. Ed.* **2010**, *49*, 46−76. (d) Soós, T. *Pure Appl. Chem.* **2011**, *83*, 667−675. (e) Stephan, D. W.; Greenberg, S.; Graham, T. W.;

Chase, P.; Hastie, J. J.; Geier, S. J.; Farrell, J. M.; Brown, C. C.; Heiden, Z. M.; Welch, G. C.; Ullrich, M. *Inorg. Chem.* **2011**, *50*, 12338−12348. (f) Stephan, D. W. *Org. Biomol. Chem.* **2012**, *10*, 5740−5746. (g) Erker, G. *Pure Appl. Chem.* **2012**, *84*, 2203−2217.

(3) de Vries, J. G., Elsevier, C. J., Eds. *The Handbook of Homogeneous Hydrogenation*; Wiley-VCH, Weinheim, 2007.

(4) (a) Chase, P. A.; Welch, G. C.; Jurca, T.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 8050−8053. (b) Spies, P.; Schwendemann, S.; Lange, S.; Kehr, G.; Fröhlich, R.; Erker, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 7543−7546. (c) Chase, P. A.; Jurca, T.; Stephan, D. W. *Chem. Commun.* **2008**, 1701−1703. (d) Chen, D.; Klankermayer, J. *Chem. Commun.* **2008**, 2130−2131. (e) Sumerin, V.; Schulz, F.; Atsumi, M.; Wang, C.; Nieger, M.; Leskelä, M.; Repo, T.; Pyykkö, P.; Rieger, B. *J. Am. Chem. Soc.* **2008**, *130*, 14117−14119. (f) Jiang, C.; Blacque, O.; Berke, H. *Chem. Commun.* **2009**, 5518−5520. (g) Rokob, T. A.; Hamza, A.; Stirling, A.; Pápai, I. *J. Am. Chem. Soc.* **2009**, *131*, 2029−2036. (h) Axenov, K. V.; Kehr, G.; Fröhlich, R.; Erker, G. *J. Am. Chem. Soc.* **2009**, *131*, 3454−3455. (i) Axenov, K. V.; Kehr, G.; Fröhlich, R.; Erker, G. *Organometallics* **2009**, *28*, 5148−5158. (j) Erős, G.; Mehdi, H.; Pápai, I.; Rokob, T. A.; Király, P.; Tárkányi, G.; Soós, T. *Angew. Chem., Int. Ed.* **2010**, *49*, 6559−6563. (k) Zhao, L.; Li, H.; Lu, G.; Huang, F.; Zhang, C.; Wang, Z.-X. *Dalton Trans.* **2011**, *40*, 1929−1937. (l) Farrell, J. M.; Hatnean, J. A.; Stephan, D. W. *J. Am. Chem. Soc.* **2012**, *134*, 15728−15731.

(5) (a) Geier, S. J.; Chase, P. A.; Stephan, D. W. *Chem. Commun.* **2010**, *46*, 4884−4886. (b) Erős, G.; Nagy, K.; Mehdi, H.; Pápai, I.; Nagy, P.; Király, P.; Tárkányi, G.; Soós, T. *Chem.—Eur. J.* **2012**, *18*, 574−585.

(6) (a) Wang, H.; Fröhlich, R.; Kehr, G.; Erker, G. *Chem. Commun.* **2008**, 5966−5968. (b) Schwendemann, S.; Tumay, T. A.; Axenov, K. V.; Peuser, I.; Kehr, G.; Fröhlich, R.; Erker, G. *Organometallics* **2010**, *29*, 1067−1069. (c) Greb, L.; Oña-Burgos, P.; Schirmer, B.; Grimme, S.; Stephan, D. W.; Paradies, J. *Angew. Chem., Int. Ed.* **2012**, *51*, 10164−10168. (d) Inés, B.; Palomas, D.; Holle, S.; Steinberg, S.; Nicasio, J. A.; Alcarazo, M. *Angew. Chem., Int. Ed.* **2012**, *51*, 12367−12369. (e) Reddy, J. S.; Xu, B.-H.; Mahdi, T.; Fröhlich, R.; Kehr, G.; Stephan, D. W.; Erker, G. *Organometallics* **2012**, *31*, 5638−5649.

(7) (a) Ménard, G.; Stephan, D. W. *J. Am. Chem. Soc.* **2010**, *132*, 1796−1797. (b) Ménard, G.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2011**, *50*, 8396−8399. (c) Xu, B.-H.; Kehr, G.; Fröhlich, R.; Wibbeling, B.; Schirmer, B.; Grimme, S.; Erker, G. *Angew. Chem., Int. Ed.* **2011**, *50*, 7183−7186. (d) Segawa, Y.; Stephan, D. W. *Chem. Commun.* **2012**, *48*, 11963−11965. (e) Mahdi, T.; Heiden, Z. M.; Grimme, S.; Stephan, D. W. *J. Am. Chem. Soc.* **2012**, *134*, 4088−4091.

(8) (a) Chen, D.; Wang, Y.; Klankermayer, J. *Angew. Chem., Int. Ed.* **2010**, *49*, 9475−9478. (b) Ghattas, G.; Chen, D.; Pan, F.; Klankermayer, J. *Dalton Trans.* **2012**, *41*, 9026−9028. (c) Sumerin, V.; Chernichenko, K.; Nieger, M.; Leskelä, M.; Rieger, B.; Repo, T. *Adv. Synth. Catal.* **2011**, *353*, 2093−2110. (d) Heiden, Z. M.; Stephan, D. W. *Chem. Commun.* **2011**, *47*, 5729−5731. For asymmetric hydrosilylation, see: (e) Chen, D.; Leich, V.; Pan, F.; Klankermayer, J. *Chem.—Eur. J.* **2012**, *18*, 5184−5187. (f) Mewald, M.; Fröhlich, R.; Oestreich, M. *Eur.—Chem. J.* **2011**, *17*, 9406−9414. (g) Mewald, M.; Oestreich, M. *Eur.—Chem. J.* **2012**, *18*, 14079−14084.

(9) For leading reviews, see: (a) Glorius, F. *Angew. Chem., Int. Ed.* **2004**, *43*, 3364−3366. (b) Johnson, J. B.; Rovis, T. *Angew. Chem., Int. Ed.* **2008**, *47*, 840−871. (c) Defieber, C.; Grützmacher, H.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4482−4502. (d) Shintani, R.; Hayashi, T. *Aldrichimica Acta* **2009**, *42*, 31−38. (e) Feng, C.-G.; Xu, M.-H.; Lin, G.-Q. *Synlett* **2011**, 1345−1356. (f) Tian, P.; Dong, H.-Q.; Lin, G.-Q. *ACS Catal.* **2012**, *2*, 95−119. (g) Feng, X.; Du, H. *Asian J. Org. Chem.* **2012**, *1*, 204−213.

(10) (a) Fischer, C.; Defieber, C.; Suzuki, T.; Carreira, E. M. *J. Am. Chem. Soc.* **2004**, *126*, 1628−1629. (b) Tokunaga, N.; Otomaru, Y.; Okamoto, K.; Ueyama, K.; Shintani, R.; Hayashi, T. *J. Am. Chem. Soc.* **2004**, *126*, 13584−13585. (c) Otomaru, Y.; Tokunaga, N.; Shintani, R.; Hayashi, T. *Org. Lett.* **2005**, *7*, 307−310. (d) Wang, Z.-Q.; Feng, C.-G.; Xu, M.-H.; Lin, G.-Q. *J. Am. Chem. Soc.* **2007**, *129*, 5336−5337. (e) Helbig, S.; Sauer, S.; Cramer, N.; Laschat, S.; Baro, A.; Frey, W. *Adv. Synth. Catal.* **2007**, *349*, 2331−2337. (f) Nishimura, T.; Nagaosa, M.; Hayashi, T. *Chem. Lett.* **2008**, *37*, 860−861. (g) Okamoto, K.; Hayashi, T.; Rawal, V. H. *Org. Lett.* **2008**, *10*, 4387−4389. (h) Shao, C.; Yu, H.-J.; Wu, N.-Y.; Feng, C.-G.; Lin, G.-Q. *Org. Lett.* **2010**, *12*, 3820−3823. (i) Brown, M. K.; Corey, E. J. *Org. Lett.* **2010**, *12*, 172−175. (j) Luo, Y.; Carnell, A. J. *Angew. Chem., Int. Ed.* **2010**, *49*, 2750−2754. (k) Pattison, G.; Piraux, G.; Lam, H. W. *J. Am. Chem. Soc.* **2010**, *132*, 14373−14375. (l) Wei, W.-T.; Yeh, J.-Y.; Kuo, T.-S.; Wu, H.-L. *Chem.—Eur. J.* **2011**, *17*, 11405−11409.

(11) (a) Hu, X.; Zhuang, M.; Cao, Z.; Du, H. *Org. Lett.* **2009**, *11*, 4744−4747. (b) Hu, X.; Cao, Z.; Liu, Z.; Wang, Y.; Du, H. *Adv. Synth. Catal.* **2010**, *352*, 651−655. (c) Cao, Z.; Du, H. *Org. Lett.* **2010**, *12*, 2602−2605. (d) Wang, Y.; Hu, X.; Du, H. *Org. Lett.* **2010**, *12*, 5482−5485.

(12) (a) Li, Q.; Dong, Z.; Yu, Z.-X. *Org. Lett.* **2011**, *13*, 1122−1125. (b) Trost, B. M.; Burns, A. C.; Tautz, T. *Org. Lett.* **2011**, *13*, 4566−4569.

(13) Spies, P.; Erker, G.; Kehr, G.; Bergander, K.; Fröhlich, R.; Grimme, S.; Stephan, D. W. *Chem. Commun.* **2007**, 5072−5074.

(14) (a) Parks, D. J.; Spence, R. E. v H.; Piers, W. E. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 809−811. (b) Parks, D. J.; Piers, W. E.; Yap, G. P. A. *Organometallics* **1998**, *17*, 5492−5503.

(15) For a recent review on transition-metal-catalyzed asymmetric homogeneous hydrogenation of imines, see: Xie, J.-H.; Zhu, S.-F.; Zhou, Q.-L. *Chem. Rev.* **2011**, *111*, 1713−1760.

(16) Hydrogenation of imines derived from *ortho*-substituted acetophenone gave less than 40% ee under the current conditions.