Synthetic Methods

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Asymmetric Ruthenium-Catalyzed Hydrogenation of 2- and 2,9-Substituted 1,10-Phenanthrolines**

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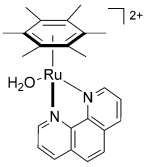
Dedicated to Professor Zhi-Tang Huang on the occasion of his 85th birthday

Asymmetric hydrogenation of heteroaromatic compounds has captured considerable attention because it offers straightforward and environmentally benign routes to optically active compounds with chiral heterocyclic skeletons.[1] Recently, various heteroarenes such as quinolines,[2] isoquinolines,[2b,3] quinoxalines,[4] indoles,[5a–h] pyrroles,[5i,j] (benzo)furans,[6] pyridines,[7] imidazoles,[8] and (benzo)thiophenes[9] have been successfully hydrogenated with high enantiomeric excesses. However, despite achievements made in this field, many challenges still remain and polycyclic heteroarenes (containing more than one heterocycle) are particularly difficult substrates.

1,10-Phenanthroline (Phen; **1**) and its derivatives containing two pyridyl rings are one of the most versatile bidentate ligands for transition-metal catalysis.[10] Much less attention has been directed toward the partially reduced 1,2,3,4-tetrahydro- and 1,2,3,4,7,8,9,10-octahydro-1,10-phenanthroline [TPhen (**2**) and OPhen (**3**), respectively] derivatives,[11–13] which are two kinds of heterocycle-containing compounds with potential bioactivity[14] and can also be used as new ligands such as vicinal diamines[15a,b] and benzimidazole-based N-heterocyclic carbenes.[15c,d] So far, few reports have focused upon heterogeneous metal-catalyzed hydrogenation[11] or reduction[12] with stoichiometric reducing agents of 1,10-phenanthroline and its derivatives, and all these methods suffered from low stereoselectivities and poor reaction yields. Moreover, as far as we know, homogeneous transition-metal catalyzed hydrogenation of such substrates has never been reported, probably because of the aromaticity, as well as the strong coordination and poisoning ability of the substrate or the reduced product. For example, the cationic half-sandwich ruthenium complex **4** containing a 1,10-phenanthroline ligand was found to be an effective catalyst for the transfer hydrogenation of ketones.[16] Expectedly, it is more challenging to realize the asymmetric reduction of substituted 1,10-phenanthrolines to selectively provide chiral TPhen and



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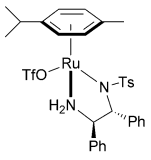
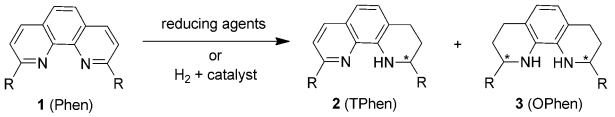


5a

OPhen (Scheme 1). To the best of our knowledge, only one example of asymmetric transfer hydrogenation of 2- and 2,9-substituted 1,10-phenanthrolines catalyzed by chiral Brønsted acid has been reported.[13] However, several obvious limitations remain, such as low reactivity or selectivity, and particularly low diastereoselectivity, as well as narrow substrate scope. Therefore, the search for new catalytic systems for the asymmetric hydrogenation of substituted 1,10-phenanthrolines is highly desirable and of great significance.



Scheme 1. Reduction of 1,10-phenanthroline and its derivatives.

During the course of our investigation into the asymmetric hydrogenation of heteroaromatic compounds, we found that cationic ruthenium complexes (such as (*R*,*R*)-**5a**[18a]; Tf = trifluoromethanesulfonyl, Ts = 4-toluenesulfonyl) containing chiral monotosylated diamine ligands[17] were very efficient catalysts for the asymmetric hydrogenation[18,19] of a broad range of quinolines[2f,g] and quinoxalines[4b] with excellent reactivity and enantioselectivity. Encouraged by these results and with our continued interest in the asymmetric hydrogenation of heteroaromatic compounds and imines,[19] we herein report the first example of the asymmetric hydrogenation of substituted 1,10-phenanthrolines using a cationic Ru-TsDPEN complex [(*R*,*R*)-**5a**]. It was found that a range of readily available 2- and 2,9-substituted 1,10-phenanthroline derivatives were successfully hydrogenated to selectively provide optically active TPhen or OPhen derivatives with unprecedented reactivity, enantioselectivity (up to > 99% *ee*), and diastereoselectivity (up to > 20:1 d.r).

In our initial study, we chose the hydrogenation of 2,9-dimethyl-1,10-phenanthroline (**1a**) as the model reaction using the cationic complex (*R*,*R*)-**5a**, which was an effective catalyst in the asymmetric hydrogenation of quinolines. It was

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found that the reaction proceeded smoothly with 1.0 mol% (*R*,*R*)-**5a** in methanol under hydrogen (50 atm) for 12 hours at room temperature. Gratifyingly, unprecedented catalytic activity, enantioselectivity, and diastereoselectivity were achieved (99% *ee* for (*R*)-**2a**, and >99% *ee* and >20:1 d.r. for (2*R*,9*R*)-**3a**) although a mixture of the chiral TPhen (*R*)-**2a** and OPhen (2*R*,9*R*)-**3a** were obtained. Notably, dehydrogenation of (2*R*,9*R*)-**3a** was observed in the presence of the ruthenium catalyst under an air atmosphere at room temperature (see below). To further understand the hydrogenation behavior, a kinetic study of the reaction was carried out by using CD_3OD as the solvent. Aliquots were taken from an active hydrogenation mixture and immediately analyzed by ^1H NMR spectroscopy. As shown in Figure 1 (see Table S1 in the Supporting Information), a clear selectivity for the hydrogenation of the first pyridyl ring at the beginning (ca. 2 h) was observed, thus providing (*R*)-**2a** as the main product with 99% *ee*. Upon prolonged reaction time, almost complete conversion was obtained to give (2*R*,9*R*)-**3a** with up to greater than 20:1 d.r. (*trans*/*cis*) and 99% *ee*. Thus, this unique hydrogenation behavior theoretically allows the synthesis of both optically active (*R*)-**2a** and (2*R*,9*R*)-**3a**.

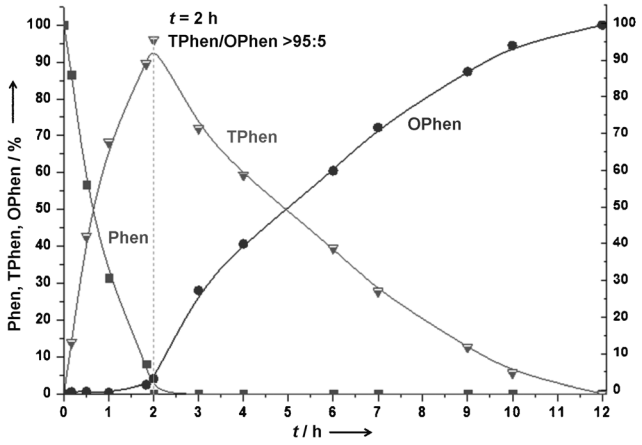


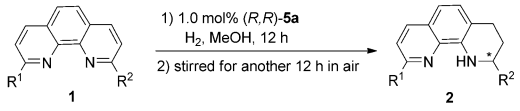
Figure 1. Reaction profiles. Reaction conditions: 2 mmol **1a** in 10 mL CD_3OD, 1.0 mol% (*R*,*R*)-**5a**, 50 atm H_2, RT.

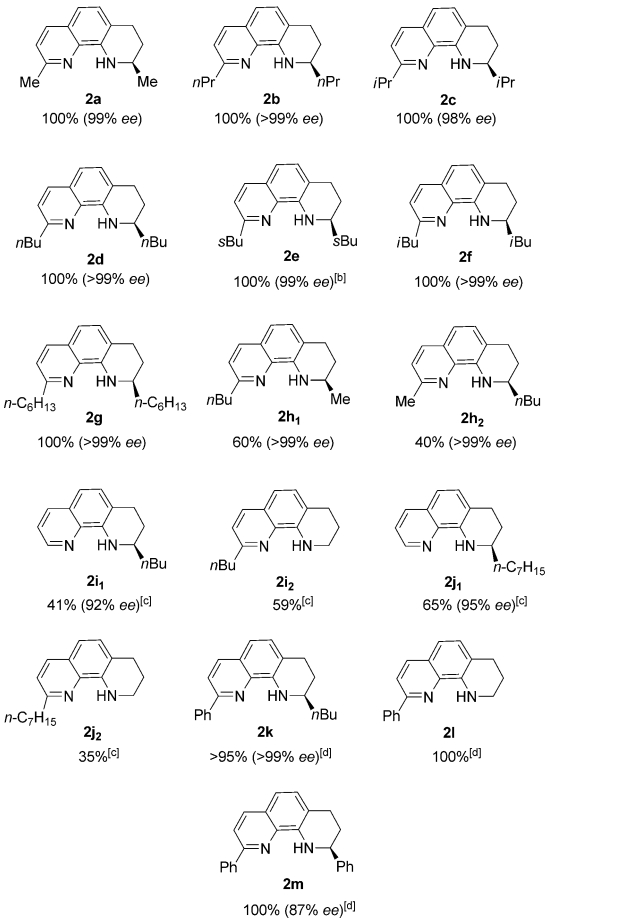
Unexpectedly, it was found that the fully reduced product OPhen could be easily dehydrogenated under an air atmosphere. A mixture of (2*R*,9*R*)-**3a** and 1.0 mol% (*R*,*R*)-**5a** in CD_3OD was stirred under an air atmosphere at room temperature for 12 hours (see Table S2 in the Supporting Information), and gave (*R*)-**2a** as the sole product with unchanged enantioselectivity (99% *ee*). On the basis of this finding, we first applied this catalytic method for the synthesis of optically active TPhen by a hydrogenation/dehydrogenation process.

To further optimize the reaction conditions, the effect of catalyst, solvent, hydrogen pressure, and reaction temperature on the asymmetric hydrogenation of **1a** was investigated. The results are collected in Tables S3 and S4 of the Supporting Information. After the screening of several ruthenium, iridium, and rhodium catalysts, the complex (*R*,*R*)-**5a** was found to be the most optimal catalyst in terms of both reactivity and enantioselectivity (entry 1 in Table S3). Notably, hydrogenation proceeded very well in a number of commonly used organic solvents and an ionic liquid with good to excellent enantioselectivities. Methanol was found to give the best result (entry 1 in Table S4). Moreover, the enantioselectivity was insensitive to hydrogen pressure and temperature (entries 9–11 in Table S4).

Under the optimized reaction conditions, hydrogenations of a variety of 2- and 2,9-substituted 1,10-phenanthroline derivatives were examined, and the results were summarized in Table 1. In combination with dehydrogenation, all substrates studied were smoothly reduced to the chiral products **2**

Table 1: Asymmetric hydrogenation of 2-substituted and 2,9-substituted 1,10-phenanthrolines catalyzed by (*R*,*R*)-**5a** to afford **2**.[a]



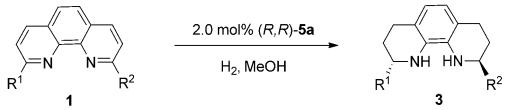


[a] Reaction conditions: 0.2 mmol substrate in 1 mL MeOH, 1.0 mol% (*R*,*R*)-**5a**, 50 atm H_2, 25 °C, 12 h. After the releasing of hydrogen, the reaction mixture was stirred for another 12 h at room temperature under air atmosphere. The yield was determined by ^1H NMR spectroscopy and enantiomeric excess (given in brackets) was determined by HPLC analysis using a chiral column (for details, see the Supporting Information). [b] Racemic **1e** was used, and attempts at separating other isomers having a chiral center at the *sec*-butyl group failed. [c] 10 atm H_2. [d] 5.0 mol% (*R*,*R*)-**5a** and 24 h.

as the sole products with excellent enantioselectivities (87 to >99% *ee*). It was found that the hydrogenation was insensitive to the steric hindrance of the alkyl side chain at both the 2- and 9-positions of Phen (**1a**–**g**). The unsymmetrical 2-alkyl- and 2,9-dialkyl-substituted 1,10-phenanthroline substrates **1h**–**j** could also give TPhen as the sole products with high enantioselectivities, albeit with low regioselectivities. In the cases of 2-alkyl-substituted 1,10-phenanthrolines, slightly lower enantioselectivities were observed. Moreover, substrates bearing one or two phenyl substituents (**1k**–**m**) could be hydrogenated under a high catalyst loading (5.0 mol%), and only the pyridyl ring bearing either an alkyl group or no substituents was reduced. Notably, 2,9-diphenyl-1,2,3,4-tetrahydro-1,10-phenanthroline (**2m**) was obtained with good enantioselectivity (87% *ee*).

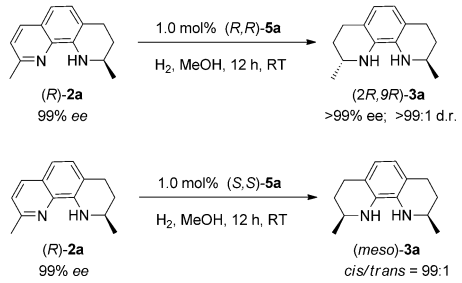
Encouraged by the above results, we subsequently investigated the synthesis of optically active chiral OPhen by direct hydrogenation of substituted 1,10-phenanthroline. It was found that the pure (2*R*,9*R*)-**3a** was stable even after exposure to air for several weeks. To avoid dehydrogenation of (2*R*,9*R*)-**3a**, the reaction mixture was poured into ice water to decompose the ruthenium catalyst after completion of the hydrogenation. With this work-up procedure, (2*R*,9*R*)-**3a** could be isolated in 90% yield with up to greater than 99% *ee* and greater than 20:1 d.r. (Table 2, entry 1). To further demonstrate the practicality of this reaction, various 2,9-dialkyl-substituted and 2-alkyl-substituted 1,10-phenanthrolines were examined by using 2.0 mol% (*R*,*R*)-**5a**. As shown in Table 2, the size of the substituents at both the 2- and 9-positions of Phen did not influence the selectivity of the reaction. Excellent diastereo- and enantioselectivities were obtained for all 2,9-dialkyl-substituted substrates studied (entries 1–8). In the cases of 2-alkyl-substituted 1,10-phenanthrolines, slightly lower enantioselectivities were observed (entries 9 and 10). Unfortunately, full hydrogenation of the two pyridyl rings of the substrates bearing phenyl substituents was not observed yet. Moreover, when (*R*)-**2a**, obtained with (*R*,*R*)-**5a** was hydrogenated by (*S*,*S*)-**5a**, *meso*-**3a** was delivered in almost quantitative yield (Scheme 2). This result indicated that the first chiral center of TPhen had no effect on the formation of the second chiral center of OPhen, which might be responsible for the extremely high diastereoselectivity achieved. Therefore, this catalytic protocol provided promising access to all isomers, including optically pure TPhen and OPhen as well as to *meso*-OPhen. In contrast, all the reported reducing systems gave a mixture of these isomers with low stereoselectivity.[11–13]

Table 2: Asymmetric hydrogenation of 2-substituted and 2,9-substituted 1,10-phenanthrolines catalyzed by (*R*,*R*)-**5a** to afford **3**.[a]



Entry	R^1/R^2	Yield [%][b]	*trans*/*cis*[c]	*ee* [%][d]
1	Me/Me (**1a**)	90	>20:1	>99 (2*R*,9*R*)
2	*n*Pr/*n*Pr (**1b**)	87	>20:1	>99 (2*R*,9*R*)
3	*i*Pr/*i*Pr (**1c**)	87	>20:1	>99 (2*S*,9*S*)
4	*n*Bu/*n*Bu (**1d**)	91	>20:1	>99 (2*R*,9*R*)
5	*s*Bu/*s*Bu (**1e**)	91	>20:1	99 (2*S*,9*S*)[e]
6	*i*Bu/*i*Bu (**1f**)	87	>20:1	>99 (2*S*,9*S*)
7	*n*-C_6H_{13}/*n*-C_6H_{13} (**1g**)	89	>20:1	>99 (2*R*,9*R*)
8	*n*Bu/Me (**1h**)	87	>20:1	>99 (2*R*,9*R*)
9	*n*Bu/H (**1i**)	89	–	98 (*R*)
10	C_7H_{15}/H (**1j**)	84	–	99 (*R*)

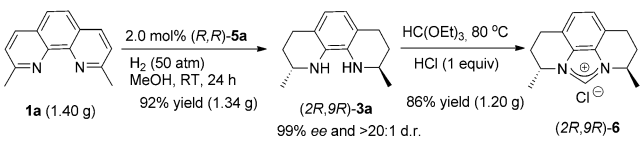
[a] Reaction conditions: 0.2 mmol substrate in 1 mL MeOH, 2.0 mol% (*R*,*R*)-**5a**, 50 atm H_2, 25 °C, 12–24 h. [b] Yields of isolated products. [c] Determined by ^{1}H NMR spectroscopy of the reduced product at low temperature or by HPLC analysis of the corresponding urea derivative (**7b**–**j** in the Supporting Information). [d] Determined by HPLC analysis of the reduced product (**3a**) or the corresponding urea derivatives with chiral columns (for details see the Supporting Information). Absolute configuration was determined by comparison of the optical rotation with literature data or by analogy. [e] Configuration of the chiral center at the *sec*-butyl group is not shown.



Scheme 2. Asymmetric hydrogenation of (*R*)-**2a** with (*R*,*R*)-**5a** and (*S*,*S*)-**5a**, respectively.

The absolute configuration of the 2,9-dibutyl-1,2,3,4,7,8,9,10-octahydro-1,10-phenanthroline (**3d**) was assigned as (2*R*,9*R*) by comparison of the optical rotation data of the corresponding urea derivative with the literature value (for details, see the Supporting Information).[13] The configurations of the other chiral products are proposed by analogy. Notably, the relative stereochemistry of the *R*-configured isomer obtained with (*R*,*R*)-**5a** is identical to that reported by us for 2-substituted tetrahydroquinolines.[2g]

Finally, we applied this new protocol to the synthesis of the chiral benzimidazolium chloride salt (2*R*,9*R*)-**6**, a precursor of chiral benzimidazole-based N-heterocyclic carbene ligands (Scheme 3). The asymmetric hydrogenation of **1a** was carried out on a gram scale (1.4 g) to give (2*R*,9*R*)-**3a** in 92% yield with 99% *ee* and greater than 99% d.r. Subsequent treatment of the optically pure (2*R*,9*R*)-**3a** with neat triethyl orthoformate and 1 equivalent of conc. HCl provided the key tetracyclic benzimidazolium chloride (2*R*,9*R*)-**6** in very good yield (86%).



Scheme 3. Synthesis of chiral-phenanthroline-derived benzimidazolium chloride salt.

In summary, we have developed the first highly enantio- and diastereoselective hydrogenation of substituted 1,10-phenanthrolines using phosphine-free chiral cationic ruthenium diamine catalysts. With our catalytic protocol, selective or full reduction of the two pyridyl rings were achieved, thus providing an efficient and practical approach for the synthesis of chiral TPhen and OPhen derivatives with excellent enantioselectivities and diastereoselectivities (up to >99% *ee* and >20:1 d.r.). These optically pure compounds are difficult to access with other methods and are of great interest in the developing of new ligands. More studies on the application of this method in the design and synthesis of new ligands and further explorations of this catalytic system for the hydrogenation of other polycyclic heteroaromatic substrates are in progress.

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[1] For reviews on asymmetric hydrogenation of heteroaromatic compounds, see: a) P. J. Dyson, *Dalton Trans.* **2003**, 2964; b) F. Glorius, *Org. Biomol. Chem.* **2005**, *3*, 4171; c) Y.-G. Zhou, *Acc. Chem. Res.* **2007**, *40*, 1357; d) R. Kuwano, *Heterocycles* **2008**, *76*, 909; e) D.-S. Wang, Q.-A. Chen, S.-M. Lu, Y.-G. Zhou, *Chem. Rev.* **2012**, *112*, 2557.

[2] For selected examples of asymmetric reduction of quinolines, see: a) W.-B. Wang, S.-M. Lu, P.-Y. Yang, X.-W. Han, Y.-G. Zhou, *J. Am. Chem. Soc.* **2003**, *125*, 10536; b) S.-M. Lu, Y.-Q. Wang, X.-W. Han, Y.-G. Zhou, *Angew. Chem.* **2006**, *118*, 2318; *Angew. Chem. Int. Ed.* **2006**, *45*, 2260; c) H. Tadaoka, D. Cartigny, T. Nagano, T. Gosavi, T. Ayad, J. P. Genêt, T. Ohshima, V. Ratovelomanana-Vidal, K. Mashima, *Chem. Eur. J.* **2009**, *15*, 9990; d) L. Xu, K. H. Lam, J. Ji, J. Wu, Q.-H. Fan, W.-H. Lo, A. S. C. Chan, *Chem. Commun.* **2005**, 1390; e) Z.-J. Wang, G.-J. Deng, Y. Li, Y.-M. He, W.-J. Tang, Q.-H. Fan, *Org. Lett.* **2007**, *9*, 1243; f) H.-F. Zhou, Z.-W. Li, Z.-J. Wang, T. L. Wang, L.-J. Xu, Y.-M. He, Q.-H. Fan, J. Pan, L.-Q. Gu, A. S. C. Chan, *Angew. Chem.* **2008**, *120*, 8592; *Angew. Chem. Int. Ed.* **2008**, *47*, 8464; g) T. L. Wang, L.-G. Zhuo, Z.-W. Li, F. Chen, Z. Ding, Y.-M. He, Q.-H. Fan, J.-F. Xiang, Z.-X. Yu, A. S. C. Chan, *J. Am. Chem. Soc.* **2011**, *133*, 9878; h) M. Rueping, A. P. Antonchick, T. Theissmann, *Angew. Chem.* **2006**, *118*, 3765; *Angew. Chem. Int. Ed.* **2006**, *45*, 3683; i) C. Wang, C. Li, X. Wu, A. Pettman, J. Xiao, *Angew. Chem.* **2009**, *121*, 6646; *Angew. Chem. Int. Ed.* **2009**, *48*, 6524.

[3] a) L. Shi, Z.-H. Ye, L.-L. Cao, R.-N. Guo, Y. Hu, Y.-G. Zhou, *Angew. Chem.* **2012**, *124*, 8411; *Angew. Chem. Int. Ed.* **2012**, *51*, 8286; b) A. Iimuro, K. Yamaji, S. Kandula, T. Nagano, Y. Kita, K. Mashima, *Angew. Chem.* **2013**, *125*, 2100; *Angew. Chem. Int. Ed.* **2013**, *52*, 2046; c) Z.-S. Ye, R.-N. Guo, X.-F. Cai, M.-W. Chen, L. Shi, Y.-G. Zhou, *Angew. Chem.* **2013**, *125*, 3773; *Angew. Chem. Int. Ed.* **2013**, *52*, 3685.

[4] For selected recent examples of asymmetric reduction of quinoxalines, see: a) W. J. Tang, L. J. Xu, Q. H. Fan, J. Wang, B. M. Fan, Z. Y. Zhou, K. H. Lam, A. S. C. Chan, *Angew. Chem.* **2009**, 121, 9299; *Angew. Chem. Int. Ed.* **2009**, *48*, 9135; b) J. Qin, F. Chen, Z. Ding, Y. He, L. Xu, Q.-H. Fan, *Org. Lett.* **2011**, *13*, 6568; c) N. Mršić, T. Jerphagnon, A. J. Minnaard, B. L. Feringa, J. G. de Vries, *Adv. Synth. Catal.* **2009**, *351*, 2549; d) D. Cartigny, T. Nagano, T. Ayad, J.-P. Genêt, T. Ohshima, K. Mashima, V. Ratovelomanana-Vidal, *Adv. Synth. Catal.* **2010**, *352*, 1886; e) S. Urban, N. Ortega, F. Glorius, *Angew. Chem.* **2011**, *123*, 3887; *Angew. Chem. Int. Ed.* **2011**, *50*, 3803; f) Q.-A. Chen, D.-S. Wang, Y.-G. Zhou, Y. Duan, H.-J. Fan, Y. Yang, Z. Zhang, *J. Am. Chem. Soc.* **2011**, *133*, 6126; g) Q.-A. Chen, K. Gao, Y. Duan, Z.-S. Ye, L. Shi, Y. Yang, Y.-G. Zhou, *J. Am. Chem. Soc.* **2012**, *134*, 2442; h) M. Rueping, F. Tato, F. R. Schoepke, *Chem. Eur. J.* **2010**, *16*, 2688.

[5] For selected examples of asymmetric reduction of indoles and pyrroles, see: a) R. Kuwano, K. Sato, T. Kurokawa, D. Karube, Y. Ito, *J. Am. Chem. Soc.* **2000**, *122*, 7614; b) R. Kuwano, K. Kaneda, T. Ito, K. Sato, T. Kurokawa, Y. Ito, *Org. Lett.* **2004**, *6*, 2213; c) R. Kuwano, M. Kashiwabara, *Org. Lett.* **2006**, *8*, 2653; d) A. Baeza, A. Pfaltz, *Chem. Eur. J.* **2010**, *16*, 2036; e) D.-S. Wang, Q.-A. Chen, W. Li, C.-B. Yu, Y.-G. Zhou, X. Zhang, *J. Am. Chem. Soc.* **2010**, *132*, 8909; f) D.-S. Wang, J. Tang, Y.-G. Zhou, M.-W. Chen, C.-B. Yu, Y. Duan, G.-F. Jiang, *Chem. Sci.* **2011**, *2*, 803; g) Y. Duan, M. W. Chen, Z.-S. Ye, D.-S. Wang, Q.-A. Chen, Y.-G. Zhou, *Chem. Eur. J.* **2011**, *17*, 7193; h) Y.-C. Xiao, C. Wang, Y. Yao, J. Sun, Y.-C. Chen, *Angew. Chem.* **2011**, *123*, 10849; *Angew. Chem. Int. Ed.* **2011**, *50*, 10661; i) R. Kuwano, M. Kashiwabara, M. Ohsumi, H. Kusano, *J. Am. Chem. Soc.* **2008**, *130*, 808; j) D.-S. Wang, Z.-S. Ye, Q.-A. Chen, Y.-G. Zhou, C.-B. Yu, H.-J. Fan, Y. Duan, *J. Am. Chem. Soc.* **2011**, *133*, 8866.

[6] For selected examples of asymmetric reduction of (benzo)furans, see: a) S. Kaiser, S. P. Smidt, A. Pfaltz, *Angew. Chem.* **2006**, *118*, 5318; *Angew. Chem. Int. Ed.* **2006**, *45*, 5194; b) P. Feiertag, M. Albert, U. Nettekoven, F. Spindler, *Org. Lett.* **2006**, *8*, 4133; c) N. Ortega, S. Urban, B. Beiring, F. Glorius, *Angew. Chem.* **2012**, *124*, 1742; *Angew. Chem. Int. Ed.* **2012**, *51*, 1710.

[7] For selected recent examples of asymmetric reduction of pyridines, see: a) F. Glorius, N. Spielkamp, S. Holle, R. Goddard, C. W. Lehmann, *Angew. Chem.* **2004**, *116*, 2910; *Angew. Chem. Int. Ed.* **2004**, *43*, 2850; b) C. Y. Legault, A. B. Charette, *J. Am. Chem. Soc.* **2005**, *127*, 8966; c) Z.-S. Ye, M.-W. Chen, Q.-A. Chen, L. Shi, Y. Duan, Y.-G. Zhou, *Angew. Chem.* **2012**, *124*, 10328; *Angew. Chem. Int. Ed.* **2012**, *51*, 10181; d) M. Rueping, A. P. Antonchick, *Angew. Chem.* **2007**, *119*, 4646; *Angew. Chem. Int. Ed.* **2007**, *46*, 4562.

[8] R. Kuwano, N. Kameyama, R. Ikeda, *J. Am. Chem. Soc.* **2011**, *133*, 7312.

[9] S. Urban, B. Beiring, N. Ortega, D. Paul, F. Glorius, *J. Am. Chem. Soc.* **2012**, *134*, 15241.

[10] For selected reviews, see: a) G. Chelucci, R. P. Thummel, *Chem. Rev.* **2002**, *102*, 3129; b) M. V. Nandakumar, S. Ghosh, C. Schneider, *Eur. J. Org. Chem.* **2009**, 6393.

[11] For examples of heterogeneous hydrogenation of 1,10-phenanthroline and its derivatives, see: a) I. F. Eckhard, R. Fielden, L. A. Summers, *Aust. J. Chem.* **1975**, *28*, 1149; b) W. M. Czaplik, J.-M. Neudörfl, A. J. von Wangelin, *Green Chem.* **2007**, *9*, 1163; c) C. Bianchini, V. D. Santo, A. Meli, S. Moneti, R. Psaro, L. Sordelli, F. Vizza, *Inorg. Chim. Acta* **2008**, *361*, 3677.

[12] For selected examples of the reduction of 1,10-phenanthroline and its derivatives with stoichiometric reducing reagents, see: a) P. C. Keller, R. L. Marks, J. V. Rund, *Polyhedron* **1983**, *2*, 595; b) A. Srikrishna, T. J. Reddy, R. Viswajanani, *Tetrahedron* **1996**, *52*, 1631; c) C. Metallinos, F. B. Barrett, Y. Wang, S. F. Xu, N. J. Taylor, *Tetrahedron* **2006**, *62*, 11145.

[13] C. Metallinos, F. B. Barrett, S. F. Xu, *Synlett* **2008**, 720.

[14] J. G. Catalano, K. S. Gudmundsson, A. Svolto, S. D. Boggs, J. F. Miller, A. Spaltenstein, M. Thomson, P. Wheelan, D. K. Minick, D. P. Phelps, S. Jenkinson, *Bioorg. Med. Chem. Lett.* **2010**, *20*, 2186.

[15] a) P. Helquist, U.S. Patent 6730788, **2004**; b) T. Irrgang, D. Friedrich, R. Kempe, *Angew. Chem.* **2011**, *123*, 2231; *Angew. Chem. Int. Ed.* **2011**, *50*, 2183; c) C. Metallinos, F. B. Barrett, J. L.

Chaytor, M. E. A. Heska, *Org. Lett.* **2004**, *6*, 3641; d) C. Metallinos, X.-D. Du, *Organometallics* **2009**, *28*, 1233.

[16] a) J. Canivet, L. Karmazin-Brelot, G. Süss-Fink, *J. Organomet. Chem.* **2005**, *690*, 3202; b) M. E. Thibault, D. V. DiMondo, M. Jennings, P. V. Abdelnur, M. N. Eberlin, M. Schlaf, *Green Chem.* **2011**, *13*, 357.

[17] For selected reviews on asymmetric transfer hydrogenation with Ru, Rh, or Ir complexes of chiral monotosylated diamines, see: a) R. Noyori, S. Hashiguchi, *Acc. Chem. Res.* **1997**, *30*, 97; b) S. Gladiali, E. Alberico, *Chem. Soc. Rev.* **2006**, *35*, 226. For pioneering contributions, see: c) S. Hashiguchi, A. Fujii, J. Takehara, T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* **1995**, *117*, 7562; d) A. Fujii, S. Hashiguchi, N. Uematsu, T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* **1996**, *118*, 2521; e) N. Uematsu, A. Fujii, S. Hashiguchi, T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* **1996**, *118*, 4916.

[18] For pioneering work on asymmetric hydrogenation using chiral metal complexes of diamine, see: a) T. Ohkuma, N. Utsumi, K. Tsutsumi, K. Murata, C. Sandoval, R. Noyori, *J. Am. Chem. Soc.* **2006**, *128*, 8724; b) C. Hedberg, K. Källström, P. I. Arvidsson, P. Brandt, P. G. Andersson, *J. Am. Chem. Soc.* **2005**, *127*, 15083; c) M. Ito, M. Hirakawa, K. Murata, T. Ikariya, *Organometallics* **2001**, *20*, 379. For recent examples, see: d) T. Ohkuma, K. Tsutsumi, N. Utsumi, N. Arai, R. Noyori, K. Murata, *Org. Lett.* **2007**, *9*, 255; e) T. Ohkuma, N. Utsumi, M. Watanabe, K. Tsutsumi, N. Arai, K. Murata, *Org. Lett.* **2007**, *9*, 2565; f) M. Ito, Y. Endo, T. Ikariya, *Organometallics* **2008**, *27*, 6053; g) T. Touge, T. Hakamata, H. Nara, T. Kobayashi, N. Sayo, T. Saito, Y. Kayaki, T. Ikariya, *J. Am. Chem. Soc.* **2011**, *133*, 14960.

[19] For selected examples of asymmetric hydrogenation of imines with metal complexes of chiral monotosylated diamines, see: a) C. Li, J. Xiao, *J. Am. Chem. Soc.* **2008**, *130*, 13208; b) C. Li, C. Wang, B. Villa-Marcos, J. Xiao, *J. Am. Chem. Soc.* **2008**, *130*, 14450; c) C. Li, B. Villa-Marcos, J. Xiao, *J. Am. Chem. Soc.* **2009**, *131*, 6967; d) S. Shirai, H. Nara, Y. Kayaki, T. Ikariya, *Organometallics* **2009**, *28*, 802; e) Y. He, Q.-H. Fan, *Org. Biomol. Chem.* **2010**, *8*, 2497; f) F. Chen, T. L. Wang, Y. He, Z. Ding, Z. Li, L. Xu, Q.-H. Fan, *Chem. Eur. J.* **2011**, *17*, 1109; g) F. Chen, Z. Ding, J. Qin, T. L. Wang, Y. He, Q.-H. Fan, *Org. Lett.* **2011**, *13*, 4348; h) Z.-Y. Ding, F. Chen, J. Qin, Y. He, Q.-H. Fan, *Angew. Chem.* **2012**, *124*, 5804; *Angew. Chem. Int. Ed.* **2012**, *51*, 5706.

