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Ruthenium-Catalyzed Hydrogenation of Carbocyclic Aromatic Amines: Access to Chiral Exocyclic Amines

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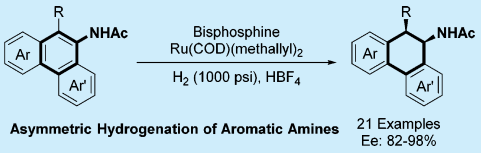
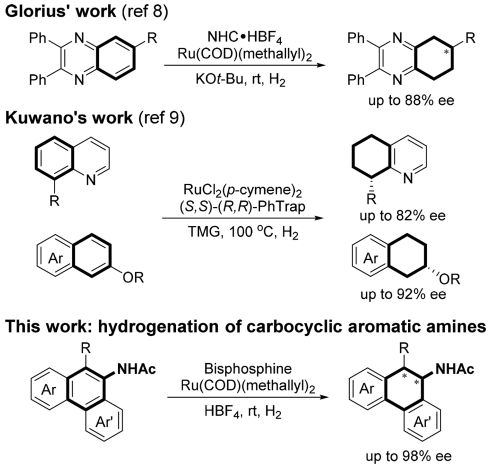
Supporting Information

ABSTRACT: The first highly enantioselective hydrogenation of carbocyclic aromatic amines has been successfully realized using *in situ*-generated chiral ruthenium complex as catalyst, affording facile access to chiral exocyclic amines with up to 98% ee.



Recently, the homogeneous asymmetric hydrogenation of heteroarenes with single and multiple heteroatoms, which provides an efficient method to structurally diverse heterocycles with high stereoselectivity, has been intensively studied.[1−3] Although considerable advances have been achieved in heterogeneous and homogeneous achiral hydrogenation of arenes in laboratory and industry, asymmetric hydrogenation of carbocyclic aromatics remains much less explored.[4,5] Several difficulties exist in this area, including the following: (a) the inherent stability resulting from aromaticity; (b) lack of a coordinating group makes stereoselectivity difficult to control; and (c) the poor discrimination of enantiotopic face creates another issue in diastereocontrol. Despite these difficulties, synthetic chemists continue to make progress in this field. For example, the selective hydrogenation of auxiliary-substituted arenes using heterogeneous catalysts provides a convenient strategy to the corresponding saturated compounds with high diastereoselectivity.[4e,6] Moreover, the hydrogenation of arenes by using ruthenium nanoparticles modified with chiral *N*-donor ligands has been tried, but no significant asymmetric induction was observed.[4c,7] Recently, asymmetric hydrogenation of carbocyclic aromatics has been successfully realized using homogeneous chiral catalysts. In 2011, Glorius' group developed the first homogeneous asymmetric hydrogenation of quinoxalines that led to the selective hydrogenation of the carbocyclic ring by using a chiral ruthenium NHC complex and up to 88% ee was obtained (see Scheme 1).[8] Subsequently, as a breakthrough, Kuwano and co-workers found that naphthalenes and quinoline carbocycles could be successfully hydrogenated by a ruthenium-PhTrap catalyst. In particular, 2-alkoxynaphthalene derivatives were converted to the corresponding chiral tetralins with up to 92% ee, despite the fact that harsh conditions were necessary (see Scheme 1).[9] Given these impressive advances, a rejuvenation of asymmetric hydrogenation of carbocyclic aromatics by exploring general catalytic system and enriching the diversity of the substrate is still challenging and highly desirable.

Scheme 1. Asymmetric Hydrogenation of Carbocyclic Aromatic Compounds



Since the aromatic stabilization of the second aromatic ring in bicyclic aromatics is somewhat lower, hydrogenation of the annulated ring is significantly facilitated.[5a,b] We reasoned that carbocyclic aromatics, such as phenanthrene and chrysene, might be suitable substrates for asymmetric hydrogenation. In addition, chiral amines are useful building blocks for construction of biologically active molecules,[10] as well as for the design of chiral ligands.[11] In view of the availability of carbocyclic aromatic amines,[12] we envisioned to realize the synthesis of chiral amines through asymmetric hydrogenation of carbocyclic aromatic amines.[13] Based on those successful experience of ruthenium-catalyzed asymmetric hydrogenation of carbocyclic aromatics[8,9] and our group's longstanding work on asymmetric hydro-

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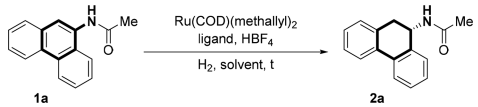
genation of *N*-containing heteroarenes,[1b,13,14] herein, we describe the first highly enantioselective and diastereoselective hydrogenation of carbocyclic aromatic amines using *in situ*-generated chiral ruthenium complexes as catalysts (see Scheme 1).

With the hypothesis in mind, *N*-(phenanthren-9-yl)acetamide (**1a**) was chosen as model substrate. We found that the treatment of 1.0 equiv of Ru(COD)(methallyl)$_2$ and 1.1 equiv of chiral bisphosphine ligands in various organic solvents with 2.0 equiv of HBF_4 at ambient temperature for ~30 min gave a ruthenium catalyst that could be used directly for the hydrogenation of **1a**. The process was derived from procedures that were developed by Heiser's group and Genêt's group.[15] Fortunately, when we tested the reaction with DuanPhos **L1** as a ligand in MeOH under hydrogen gas (600 psi) at 60 °C, **2a** was obtained with 92% ee and 42% yield (Table 1, entry 1). Notably,

Table 1. Evaluation of Reaction Parameters[a]



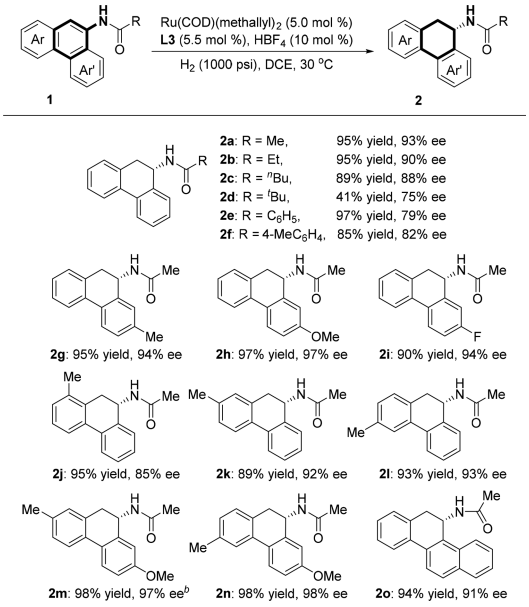
entry	solvent	ligand	temp, *t* (°C)	yield[b] (%)	ee[c] (%)
1	MeOH	**L1**	60	42	92 (*S*)
2	EtOH	**L1**	60	51	91 (*S*)
3	^{i}PrOH	**L1**	60	48	88 (*S*)
4	DCM	**L1**	60	44	79 (*S*)
5	DCE	**L1**	60	44	91 (*S*)
6	EtOAc	**L1**	60	47	88 (*S*)
7	THF	**L1**	60	39	73 (*S*)
8	toluene	**L1**	60		
9	DCE	**L2**	60	49	82 (*R*)
10	DCE	**L3**	60	88	86 (*S*)
11	DCE	**L4**	60	88	56 (*R*)
12	DCE	**L5**	60	84	06 (*R*)
13	DCE	**L6**	60	95	41 (*R*)
14	DCE	**L7**	60	55	52 (*S*)
15	DCE	**L8**	60	68	83 (*S*)
16[d]	DCE	**L3**	60	95	84 (*S*)
17[d]	DCE	**L3**	30	95	88 (*S*)
18[d,e]	DCE	**L3**	30	95	93 (*S*)

[a]Conditions: **1a** (0.10 mmol), Ru(COD)(methallyl)$_2$ (2 mol %), ligand (2.2 mol %), HBF_4 (4.0 mol %), H_2 (600 psi), solvent (2.0 mL), 60 °C, 24 h. [b]Determined by ^{1}H NMR, using 1,3,5-trimethoxybenzene as an internal standard. [c]Enantiomeric excess (ee), determined via HPLC. [d]Ru(COD)(methallyl)$_2$ (5 mol %), **L3** (5.5 mol %), HBF_4 (10 mol %). [e]H_2 (1000 psi). DCM = CH_2Cl_2, DCE = $ClCH_2CH_2Cl$.

the catalytic system was compatible with a series of solvents, but deacetylation product was observed in alcoholic solvents (Table 1, entries 1−7). In terms of enantioselectivity and yield, dichloroethane (DCE) was chosen as the optimal solvent (Table 1, entry 5). Next, some commercially available chiral bisphosphine ligands were evaluated. Electron-rich ligands were favored and the best result was achieved with DuPhos **L3** (88% yield, 86% ee; see Table 1, entry 10). In order to enhance the activity of the reaction, the catalyst loading was increased to 5 mol % with significantly improved activity and slightly reduced enantioselectivity (Table 1, entry 16). To our delight, when reaction temperature was decreased to 30 °C and hydrogen pressure was increased to 1000 psi, 95% yield and 93% ee were obtained (Table 1, entry 18). Therefore, the optimal condition was established: Ru(COD)(methallyl)$_2$/**L3**/HBF_4 as the catalyst, DCE as the solvent, hydrogen gas (1000 psi) and a reaction temperature of 30 °C.

After establishing the optimal condition, we investigated the substrate scope, and the results are summarized in Scheme 2.

Scheme 2. Substrate Scope: Carbocyclic Aromatic Amines[a]



[a]Conditions: **1** (0.20 mmol), Ru(COD)(methallyl)$_2$ (5 mol %), **L3** (5.5 mol %), HBF_4 (10 mol %), H_2 (1000 psi), DCE (2.0 mL), 30 °C, 24 h. Isolated yields. [b]DCE (3.0 mL).

Different substituents on the amide group were tested and linear alkyl and aryl groups were suitable substituents, affording moderate to excellent results, but sterically hindered tertiary butyl was unfavorable (Scheme 2, **2a**−**2f**). The electronic effect of annulated ring displayed little concern with activities (Scheme 2, **2g**−**2i**). Pleasingly, when the methoxy group was introduced at the 7-position of the phenanthrene ring, 97% ee was obtained (Scheme 2, **2h**). Moreover, the effect of methyl position of annulated ring was also screened (Scheme 2, **2j**−**2n**). When the methyl group was introduced at the 1-position of phenanthrene ring, a slightly low ee value (85%) was obtained (Scheme 2, **2j**). The asymmetric hydrogenation of *N*-(chrysen-5-yl)acetamide **1o** was also evaluated; the reaction also transformed completely and an excellent ee value (91%) was obtained (Scheme 2, **2o**).

Next, asymmetric hydrogenation of more-challenging disubstituted carbocyclic aromatic amines was explored. Considering the difficulty in activity and stereocontrol, hydrogenation conditions were further optimized. A survey of solvents indicated that ^{i}PrOH was the best choice, albeit with low activity and moderate enantioselectivity. It is noteworthy that excellent diastereoselectivity was achieved, regardless of the solvent used (Table 2, entries 1−5). To further improve the reaction efficiency, an enhanced survey of the chiral bisphosphine ligands was conducted; electron-rich JosiPhos **L6** proved to be the most favorable ligand, in terms of excellent yield, albeit with 77% ee see (Table 2, entries 6−8). When we reduced the temperature to 30 °C, the ee value could be increased to 83% (Table 2, entry 9). Therefore, the optimal reaction condition was established: Ru(COD)(methallyl)$_2$/**L6**/HBF_4 as the catalyst, ^{i}PrOH as the solvent, hydrogen gas (1000 psi), and a reaction temperature of

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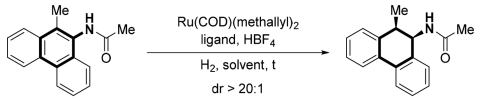
Table 2. Optimization of Reaction Conditions[a]



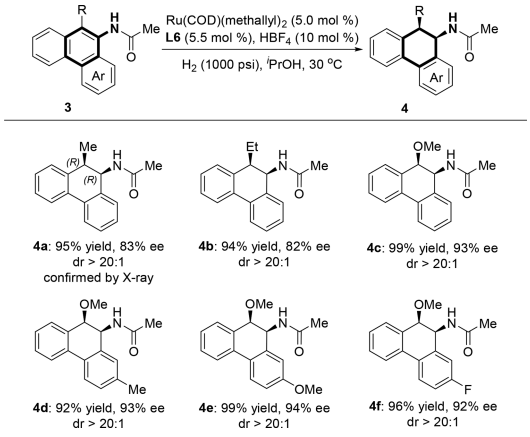
entry	solvent	ligand	yield[b] (%)	ee[c] (%)
1	MeOH	**L3**	26	61 (*S*,*S*)
2	EtOH	**L3**	40	69 (*S*,*S*)
3	^{i}PrOH	**L3**	46	72 (*S*,*S*)
4	DCM	**L3**	44	57 (*S*,*S*)
5	DCE	**L3**	38	55 (*S*,*S*)
6	^{i}PrOH	**L2**	19	90 (*R*,*R*)
7	^{i}PrOH	**L5**	87	35 (*R*,*R*)
8	^{i}PrOH	**L6**	>99	77 (*R*,*R*)
9[d]	^{i}PrOH	**L6**	>99	83 (*R*,*R*)

[a]Conditions: **3a** (0.10 mmol), Ru(COD)(methallyl)$_2$ (5 mol %), **L** (5.5 mol %), HBF$_4$ (10 mol %), H$_2$ (1000 psi), solvent (2.0 mL), 60 °C, 24 h. Isolated yields. [b]Determined by ^{1}H NMR. [c]Determined by HPLC. [d]At 30 °C.

30 °C. The absolute configuration of product **4a** (which could be increased to 99% ee by a recrystallization with dichloromethane and *n*-hexane) was unambiguously determined to be (*R*,*R*) by X-ray crystallographic analysis (see the Supporting Information).

Having identified the optimal reaction conditions, we then investigated the substrate scope and the results were depicted in Scheme 3. Changing the methyl to ethyl group, 82% ee and 94%

Scheme 3. Substrate Scope: *ortho*-Substituted Aromatic Amines[a]

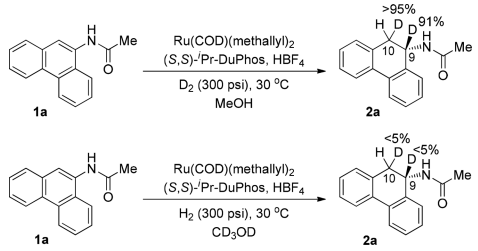


[a]Conditions: **3** (0.20 mmol), Ru(COD)(methallyl)$_2$ (5 mol %), **L6** (5.5 mol %), HBF$_4$ (10 mol %), H$_2$ (1000 psi), ^{i}PrOH (4.0 mL), 30 °C, 24 h. Isolated yields.

yield was obtained (see **4b** in Scheme 3). Fortunately, when we introduced a methoxy group adjacent to amide group, excellent enantioselectivity (93% ee) was obtained (see **4c** in Scheme 3). In addition, the electronic effect of annulated ring displayed little concern with activities and enantioselectivities (see **4d**–**4f** in Scheme 3).

To gain insight into the reaction process, two isotopic labeling experiments were carried out. When **1a** was subjected to the asymmetric hydrogenation with D$_2$, ^{1}H NMR analysis of the crude hydrogenation product showed that one D atom was incorporated into the 9-position with 91% and into 10-position with >95%. When the asymmetric hydrogenation was carried out in CD$_3$OD, the D atoms were incorporated to the 9-position and 10-position with <5%, respectively (see Scheme 4). The above

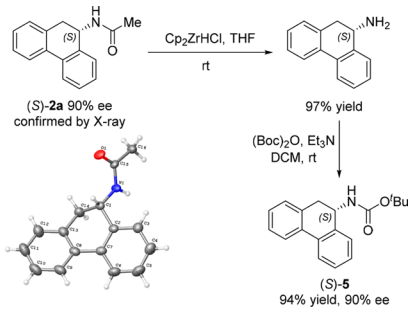
Scheme 4. Deuterium Labeling Experiments



experiments suggested that the hydrogenation pathway is direct hydrogenation of carbon–carbon double bond of enamide moiety: the tautomerization process of enamide to ketimine intermediate is not involved.

To demonstrate the practical utility of the above methodology, scaleup of the asymmetric hydrogenation was tested and conducted smoothly with retained enantioselectivity (see the Supporting Information). Meanwhile, deacetylation reaction of **2a** was carried out and furnished the chiral exocyclic amine **5** with retained enantioselectivity and 94% yield (Scheme 5). The

Scheme 5. X-ray Structure of (*S*)-2a and Deacetylation



absolute configuration of the product **2a** (which could be upgraded to 99% ee by a simple recrystallization with dichloromethane and *n*-hexane) was unambiguously assigned to be *S* by X-ray crystallographic analysis.

In summary, we have successfully realized the first highly asymmetric hydrogenation of carbocyclic aromatic amines using an *in situ*-generated chiral ruthenium as catalyst under mild conditions, providing an efficient and facile access to chiral exocyclic amines with up to 98% of enantioselectivity. Studies to extend the strategy to various carbocyclic aromatic compounds are ongoing in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b04060.

Experimental procedures, characterization data, and NMR spectra (PDF)

Accession Codes

CCDC 1563447–1563448 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) For reviews, see: (a) Glorius, F. *Org. Biomol. Chem.* **2005**, *3*, 4171. (b) Zhou, Y.-G. *Acc. Chem. Res.* **2007**, *40*, 1357. (c) Kuwano, R. *Heterocycles* **2008**, *76*, 909. (d) Yu, Z.; Jin, W.; Jiang, Q. *Angew. Chem., Int. Ed.* **2012**, *51*, 6060. (e) Wang, D.-S.; Chen, Q.-A.; Lu, S.-M.; Zhou, Y.-G. *Chem. Rev.* **2012**, *112*, 2557. (f) Chen, Q.-A.; Ye, Z.-S.; Duan, Y.; Zhou, Y.-G. *Chem. Soc. Rev.* **2013**, *42*, 497. (g) Zhao, D.; Glorius, F. *Angew. Chem., Int. Ed.* **2013**, *52*, 9616. (h) Ye, Z.-S.; Shi, L.; Zhou, Y.-G. *Synlett* **2014**, *25*, 928. (i) He, Y.-M.; Song, F.-T.; Fan, Q.-H. *Top. Curr. Chem.* **2013**, *343*, 145. (j) Balakrishna, B.; Núñez-Rico, J. L.; Vidal-Ferran, A. *Eur. J. Org. Chem.* **2015**, *2015*, 5293. (k) Zhao, D.; Candish, L.; Paul, D.; Glorius, F. *ACS Catal.* **2016**, *6*, 5978.

(2) For selected examples on metallocatalytic hydrogenation, see: (a) Kuwano, R.; Sato, K.; Kurokawa, T.; Karube, D.; Ito, Y. *J. Am. Chem. Soc.* **2000**, *122*, 7614. (b) Wang, W.-B.; Lu, S.-M.; Yang, P.-Y.; Han, X.-W.; Zhou, Y.-G. *J. Am. Chem. Soc.* **2003**, *125*, 10536. (c) Legault, C. Y.; Charette, A. B. *J. Am. Chem. Soc.* **2005**, *127*, 8966. (d) Kaiser, S.; Smidt, S. P.; Pfaltz, A. *Angew. Chem., Int. Ed.* **2006**, *45*, 5194. (e) Kuwano, R.; Kashiwabara, M.; Ohsumi, M.; Kusano, H. *J. Am. Chem. Soc.* **2008**, *130*, 808. (f) Zhou, H.; Li, Z.; Wang, Z.; Wang, T.; Xu, L.; He, Y.; Fan, Q.-H.; Pan, J.; Gu, L.; Chan, A. S. C. *Angew. Chem., Int. Ed.* **2008**, *47*, 8464. (g) Wang, D.-S.; Chen, Q.-A.; Li, W.; Yu, C.-B.; Zhou, Y.-G.; Zhang, X. *J. Am. Chem. Soc.* **2010**, *132*, 8909. (h) Wang, D.-S.; Ye, Z.-S.; Chen, Q.-A.; Zhou, Y.-G.; Yu, C.-B.; Fan, H.-J.; Duan, Y. *J. Am. Chem. Soc.* **2011**, *133*, 8866. (i) Wang, T.; Zhuo, L.-G.; Li, Z.; Chen, F.; Ding, Z.; He, Y.; Fan, Q.-H.; Xiang, J.; Yu, Z.-X.; Chan, A. S. C. *J. Am. Chem. Soc.* **2011**, *133*, 9878. (j) Ortega, N.; Urban, S.; Beiring, B.; Glorius, F. *Angew. Chem., Int. Ed.* **2012**, *51*, 1710. (k) Wang, T.; Chen, F.; Qin, J.; He, Y.-M.; Fan, Q.-H. *Angew. Chem., Int. Ed.* **2013**, *52*, 7172. (l) Duan, Y.; Li, L.; Chen, M.-W.; Yu, C.-B.; Fan, H.-J.; Zhou, Y.-G. *J. Am. Chem. Soc.* **2014**, *136*, 7688. (m) Zhang, J.; Chen, F.; He, Y.-M.; Fan, Q.-H. *Angew. Chem., Int. Ed.* **2015**, *54*, 4622. (n) Wei, X.; Qu, B.; Zeng, X.; Savoie, J.; Fandrick, K. R.; Desrosiers, J.-N.; Tcyrulnikov, S.; Marsini, M. A.; Buono, F. G.; Li, Z.; Yang, B.-S.; Tang, W.; Haddad, N.; Gutierrez, O.; Wang, J.; Lee, H.; Ma, S.; Campbell, S.; Lorenz, J. C.; Eckhardt, M.; Himmelsbach, F.; Peters, S.; Patel, N. D.; Tan, Z.; Yee, N. K.; Song, J. J.; Roschangar, F.; Kozlowski, M. C.; Senanayake, C. H. *J. Am. Chem. Soc.* **2016**, *138*, 15473. (o) Tosatti, P.; Pfaltz, A. *Angew. Chem., Int. Ed.* **2017**, *56*, 4579. (p) Li, W.; Wiesenfeldt, M. P.; Glorius, F. *J. Am. Chem. Soc.* **2017**, *139*, 2585.

(3) For selected examples on organocatalytic reduction of heteroarenes, see: (a) Rueping, M.; Antonchick, A. P.; Theissmann, T. *Angew. Chem., Int. Ed.* **2006**, *45*, 3683. (b) Rueping, M.; Antonchick, A. P. *Angew. Chem., Int. Ed.* **2007**, *46*, 4562. (c) Guo, Q.-S.; Du, D.-M.; Xu, J. *Angew. Chem., Int. Ed.* **2008**, *47*, 759. (d) Chen, Q.-A.; Wang, D.-S.; Zhou, Y.-G.; Duan, Y.; Fan, H.-J.; Yang, Y.; Zhang, Z. *J. Am. Chem. Soc.* **2011**, *133*, 6126. (e) Chen, Q.-A.; Gao, K.; Duan, Y.; Ye, Z.-S.; Shi, L.; Yang, Y.; Zhou, Y.-G. *J. Am. Chem. Soc.* **2012**, *134*, 2442. (f) Chen, M.-W.; Cai, X.-F.; Chen, Z.-P.; Shi, L.; Zhou, Y.-G. *Chem. Commun.* **2014**, *50*, 12526. (g) Shugrue, C. R.; Miller, S. J. *Angew. Chem., Int. Ed.* **2015**, *54*, 11173. (h) Wang, J.; Chen, M.-W.; Ji, Y.; Hu, S.-B.; Zhou, Y.-G. *J. Am. Chem. Soc.* **2016**, *138*, 10413.

(4) For reviews, see: (a) Dyson, P. J. *Dalton Trans.* **2003**, 2964. (b) Maegawa, T.; Akashi, A.; Yaguchi, K.; Iwasaki, Y.; Shigetsura, M.; Monguchi, Y.; Sajiki, H. *Chem.—Eur. J.* **2009**, *15*, 6953. (c) Gual, A.; Godard, C.; Castillón, S.; Claver, C. *Dalton. Trans.* **2010**, *39*, 11499. (d) Giustra, Z. X.; Ishibashi, J. S. A.; Liu, S.-Y. *Coord. Chem. Rev.* **2016**, *314*, 134. (e) Gualandi, A.; Savoia, D. *RSC Adv.* **2016**, *6*, 18419.

(5) For selected examples on homogeneous hydrogenation of benzene rings by using achiral catalysts, see: (a) Grey, R. A.; Pez, G. P.; Wallo, A. *J. Am. Chem. Soc.* **1980**, *102*, 5948. (b) Borowski, A. F.; Sabo-Etienne, S.; Donnadieu, B.; Chaudret, B. *Organometallics* **2003**, *22*, 1630. (c) Wei, Y.; Rao, B.; Cong, X.; Zeng, X. *J. Am. Chem. Soc.* **2015**, *137*, 9250. (d) Li, H.; Wang, Y.; Lai, Z.; Huang, K.-W. *ACS Catal.* **2017**, *7*, 4446. (e) Wiesenfeldt, M. P.; Nairoukh, Z.; Li, W.; Glorius, F. *Science* **2017**, *357*, 908.

(6) For selected examples on diastereoselective hydrogenation of aromatics bearing a chiral auxiliary, see: (a) Besson, M.; Blanc, B.; Champelet, M.; Gallezot, P.; Nasar, K.; Pinel, C. *J. Catal.* **1997**, *170*, 254. (b) Besson, M.; Neto, S.; Pinel, C. *Chem. Commun.* **1998**, 1431. (c) Ranade, V. S.; Prins, R. *J. Catal.* **1999**, *185*, 479. (d) Besson, M.; Delbecq, F.; Gallezot, P.; Neto, S.; Pinel, C. *Chem.—Eur. J.* **2000**, *6*, 949. (e) Heitbaum, M.; Fröhlich, R.; Glorius, F. *Adv. Synth. Catal.* **2010**, *352*, 357.

(7) For selected examples on hydrogenation of arenes using ruthenium nanoparticles modified with chiral ligands, see: (a) Jansat, S.; Picurelli, D.; Pelzer, K.; Philippot, K.; Gómez, M.; Muller, G.; Lecante, P.; Chaudret, B. *New J. Chem.* **2006**, *30*, 115. (b) Gual, A.; Axet, M. R.; Philippot, K.; Chaudret, B.; Denicourt-Nowicki, A.; Roucoux, A.; Castillon, S.; Claver, C. *Chem. Commun.* **2008**, 2759.

(8) Urban, S.; Ortega, N.; Glorius, F. *Angew. Chem., Int. Ed.* **2011**, *50*, 3803.

(9) (a) Kuwano, R.; Morioka, R.; Kashiwabara, M.; Kameyama, N. *Angew. Chem., Int. Ed.* **2012**, *51*, 4136. (b) Kuwano, R.; Ikeda, R.; Hirasada, K. *Chem. Commun.* **2015**, *51*, 7558.

(10) (a) Welch, W. M.; Kraska, A. R.; Sarges, R.; Koe, B. K. *J. Med. Chem.* **1984**, *27*, 1508. (b) Ahlskog, J. E.; Muenter, M. D.; Bailey, P. A.; Miller, P. M. *Clin. Neuropharmacol.* **1991**, *14*, 214. (c) Höhne, M.; Bornscheuer, U. T. *ChemCatChem* **2009**, *1*, 42. (d) Nugent, T. C.; El-Shazly, M. *Adv. Synth. Catal.* **2010**, *352*, 753.

(11) (a) Irurre, J.; Riera, M.; Guixá, M. *Chirality* **2002**, *14*, 490. (b) Lin, S.-Z.; You, T.-P. *Synth. Commun.* **2009**, *39*, 4133.

(12) (a) Benesch, L.; Bury, P.; Guillaneux, D.; Houldsworth, S.; Wang, X.; Snieckus, V. *Tetrahedron Lett.* **1998**, *39*, 961. (b) Voth, S.; Hollett, J. W.; McCubbin, J. A. *J. Org. Chem.* **2015**, *80*, 2545. (c) Yoshimura, F.; Abe, T.; Tanino, K. *Org. Lett.* **2016**, *18*, 1630.

(13) For examples on enantioselective reduction of heteroaromatic amines, quinolin-3-amines, see: (a) Cai, X.-F.; Huang, W.-X.; Chen, Z.-P.; Zhou, Y.-G. *Chem. Commun.* **2014**, *50*, 9588. (b) Cai, X.-F.; Guo, R.-N.; Feng, G.-S.; Wu, B.; Zhou, Y.-G. *Org. Lett.* **2014**, *16*, 2680. (c) Cai, X.-F.; Guo, R.-N.; Chen, M.-W.; Shi, L.; Zhou, Y.-G. *Chem.—Eur. J.* **2014**, *20*, 7245.

(14) (a) Shi, L.; Ye, Z.-S.; Cao, L.-L.; Guo, R.-N.; Hu, Y.; Zhou, Y.-G. *Angew. Chem., Int. Ed.* **2012**, *51*, 8286. (b) Ye, Z.-S.; Chen, M.-W.; Chen, Q.-A.; Shi, L.; Duan, Y.; Zhou, Y.-G. *Angew. Chem., Int. Ed.* **2012**, *51*, 10181. (c) Ye, Z.-S.; Guo, R.-N.; Cai, X.-F.; Chen, M.-W.; Shi, L.; Zhou, Y.-G. *Angew. Chem., Int. Ed.* **2013**, *52*, 3685. (d) Guo, R.-N.; Cai, X.-F.; Shi, L.; Ye, Z.-S.; Chen, M.-W.; Zhou, Y.-G. *Chem. Commun.* **2013**, *49*, 8537. (e) Huang, W.-X.; Yu, C.-B.; Shi, L.; Zhou, Y.-G. *Org. Lett.* **2014**, *16*, 3324. (f) Huang, W.-X.; Yu, C.-B.; Ji, Y.; Liu, L.-J.; Zhou, Y.-G. *ACS Catal.* **2016**, *6*, 2368.

(15) (a) Genêt, J. P.; Mallart, S.; Pinel, C.; Juge, S.; Laffitte, J. A. *Tetrahedron: Asymmetry* **1991**, *2*, 43. (b) Heiser, B.; Broger, E. A.; Crameri, Y. *Tetrahedron: Asymmetry* **1991**, *2*, 51.

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