ChemComm

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: Y. Li, M. Lei, W. Yuan, E. Meggers and L. Gong, *Chem. Commun.*, 2017, DOI: 10.1039/C7CC04691J.

ROYAL SOCIETY OF CHEMISTRY

rsc.li/chemcomm

View Article Online
DOI: 10.1039/C7CC04691J

ChemComm

COMMUNICATION

An *N*-Heterocyclic Carbene Iridium Catalyst with Metal-Centered Chirality for Enantioselective Transfer Hydrogenation of Imines

Yanjun Li,[a] Meng Lei,[a] Wei Yuan,[a] Eric Meggers[a,b] and Lei Gong*[a]

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/chemcomm

A cyclometalating *N*-heterocyclic carbene iridium complex featuring metal-centered chirality was designed and applied to the asymmetric transfer hydrogenation (ATH) of imines. Four strongly σ-donating carbon-based substituents (2 carbenes and 2 phenyl moieties), a chirality transfer directly from the stereogenic metal center to the C=N bond of substrates, as well as a restriction of catalyst deactivation by steric demanding substituents, render the new complex one of the most efficient catalysts for ATH of cyclic *N*-sulfonylimines (down to 0.01 mol% cat., 24 examples, 94–98% ee).

Transition-metal-catalyzed asymmetric transfer hydrogenation (ATH) of imines provides straightforward access to chiral amines and has attracted great attention owing to the simplified operation, sustainability and possible industrial applications.[1,2] Such reactions have been enabled by Ru, Rh, Ir or Fe-based catalysts, often in combination with a chiral diamine ligand. However, in contrast to the reduction of ketones or olefins, they are much less effective regarding the substrate scope, catalyst loading and stereoselectivity.[3] The drawbacks of imine ATH reactions include: 1) catalyst poisoning through metal coordination of imines or amines; 2) intrinsic reactivity of imines toward hydrolysis, formation of (hemi)aminals with amines or *N,O*-acetals with alchols; 3) decline of enantioselectivities raised by the *Z*/*E* isomerization of acyclic imines; 4) an often complex reaction mechanism.[4–7] Consequently, the design of new catalysts with different structures for ATH of imines remains a challenging task, while at the same time is of great importance for fundamental studies and practical applications.[8]

N-heterocyclic carbene (NHC) complexes have been established as potentially highly useful catalysts in transfer hydrogenations.[9] However, much less success has been achieved when applied in an asymmetric fashion.[10] To the best of our knowledge, the catalytic ATH reaction of imines by a chiral metal carbene catalyst has not been reported thus far. Recently, our groups developed one class of chiral-only-at-metal Lewis acid catalysts in which the asymmetric induction occurs directly from the metal to the substrates and provides powerful stereocontrol for a range of organic transformations.[11,12] We were wondering if utilizing such a strategy to assemble NHC ligands around a central metal would lead to the discovery of highly active and enantioselective catalysts for ATH of imines (Fig. 1a). The use of chelating carbene ligands with strong σ-donor ability is presumably not only beneficial for enhancing reactivity of the metal hydride intermediates during the catalysis,[13] but also capable of stabilizing the configuration of the catalyst as suggested by a recent study.[14]

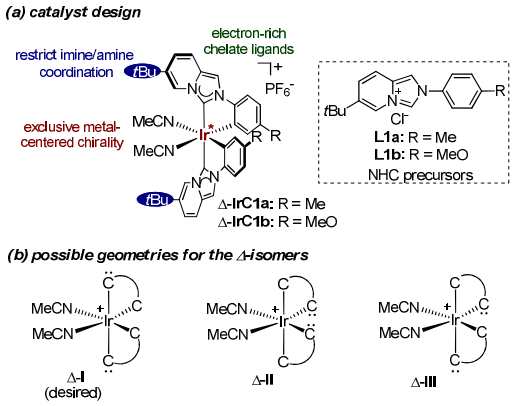


Fig. 1 Catalyst design.

We have demonstrated that a co-catalyst system consisting of a chiral-at-metal complex and a pyrazole additive was effective for the enantioselective transfer hydrogenation of acetophenones and some other aromatic ketones.[11f] However, only very sluggish catalytic outcomes were achieved when applied to the reduction of imines. The potential issue of catalyst deactivation, combined with Crabtree's observation that the complex [Ir(bis-NHC)(OAc)I_2] exhibited prominent activity for hydride transfer,[15] gave rise to our consideration to develop chiral iridium catalysts based on a chelating carbene scaffold.[16] After primary experiments on ligand

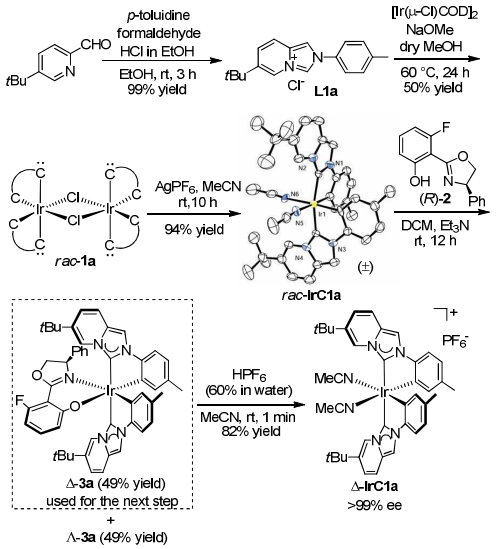
[a] College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, People's Republic of China. Email: gongl@xmu.edu.cn
[b] Philipps-Universität Marburg, Hans-Meerwein-Strasse 4, 35043 Marburg, Germany

Electronic Supplementary Information (ESI) available: Experimental details and analytical data. See DOI: 10.1039/x0xx00000x

View Article Online
DOI: 10.1039/C7CC04691J

screening, we selected **L1a–b** as the carbene precursors[17] for the construction of propeller-type complexes with an exclusive metal-centered chirality (Fig. 1a). In theory, six possible propeller-type geometries (Δ-**I**, Δ-**II**, Δ-**III** and their enantiomers) exist for this type of complexes (Fig. 1b), while the C_2-symmetric Δ-**I** and Λ-**I** are the most interesting ones in view that the steric demanding *tert*-butyl groups locating at the top and bottom of catalytic active sites would be beneficial for chirality transfer and restriction of amines/imines coordination. Therefore, it is critical to control both the relative and absolute stereochemistry during the synthesis.

The chiral catalysts were prepared through a straightforward route as demonstrated for Δ-**IrC1a** in Scheme 1. Accordingly, Imidazolium salt **L1a** synthesized by a one-step procedure was reacted with $[Ir(\mu\text{-Cl})(COD)]_2$ at 60 °C for 24 h to afford dimeric complex *rac*-**1a** (Scheme 1). As the key step of diastereoselective synthesis, the cyclometalation was significantly temperature-dependant. Above 70 °C, the undesired isomers were also obtained. Subsequently, *rac*-**1a** was converted to the racemic catalyst *rac*-**IrC1a** in 94% yield by treatment with $AgPF_6$ in MeCN at room temperature for 10 h. A crystal structure confirmed its geometry of two carbene carbons locating at the positions *trans* to each other.[18] Finally, an enantiopure version of the catalyst, namely Δ-**IrC1a**, was obtained with > 99% *ee* through an auxiliary-mediated method.[19]

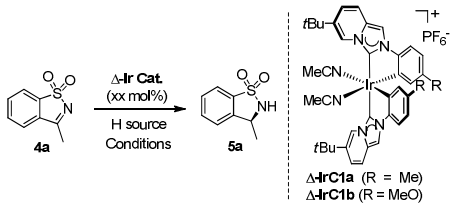


Scheme 1 Synthetic route to the non-racemic catalyst Δ-**IrC1a**.

With the desired catalyst in hand, we next examined its properties regarding ATH of imines. Cyclic *N*-sulfonylimines were chosen as the substrates, considering that: 1) enantioselective reduction of cyclic *N*-sulfonylimines is the most straightforward strategy to obtain chiral sultams, which are important synthetic targets existing in a wide range of biologically active compounds;[20] 2) to date, only TsDPEN-Ru-type complexes[21] and a binapine-nickel catalyst[2e] were reported for ATH of cyclic *N*-sulfonylimines, while typically performing with narrow substrate scope and catalyst loadings higher than 1 mol% to achieve enantioselectivities above 90%. Hence, the development of an efficient and general method for the synthesis of optically active sultams is highly desirable.[22,23]

The transfer hydrogenation of **4a** with ammonium formate was investigated as a model system (Table 1). Encouragingly, in the presence of 0.5 mol% Δ-**IrC1a** in THF/H_2O (1:1) at 50 °C, **5a** was provided in 64% conversion and with 93% ee in 6 h (entry 1). The reaction was significantly dependent on the solvents (see more details in the ESI), of which the best rate and enantioselectivity were achieved in DMF/H_2O (2:1, entry 2). The catalyst still exhibited great efficiency and stereocontrol at lower loadings (entries 3–6). For example, in the presence of only 0.05 mol% of Δ-**IrC1a** and at 60 °C, **5a** was obtained in 91% conversion and with 98% ee within 5 h (entry 4). A further reduction to 0.02 or 0.01 mol% led to a somewhat decrease of rate and enantioselectivity (entries 5, 6). As a comparison, a methoxy derivative complex Δ-**IrC1b** and previously developed Lewis acids Δ-**IrO**, Δ-**IrS**[11a,b] were tested in the catalysis. Δ-**IrS** was significantly less beneficial (entry 4 *vs.* entry 7), while Δ-**IrO** only provide trace amounts of product (entries 8, 9). Replacing ammonium formate by sodium formate or HCO_2H/Et_3N (5:2) as the reductant led to sluggish transformation (entries 10, 11), suggesting that the ammonium ion might play an important role. To confirm this assumption, we monitored the reaction under the optimal conditions without addition of the substrate. A new species was successfully isolated and identified to be a derivative complex with two coordinated ammonia Δ-**6** (Scheme 2), which provided almost identical activity in the reaction of **4a**→**5a** (entry 12). In addition, complex Δ-**6** would slowly decompose when left under vacuum, most likely by affording a 16-electron mono-ammonia complex according to HRMS analysis and a recent work by Nolan *et. al*.[24]

Table 1 Optimization of reaction conditions.[a]



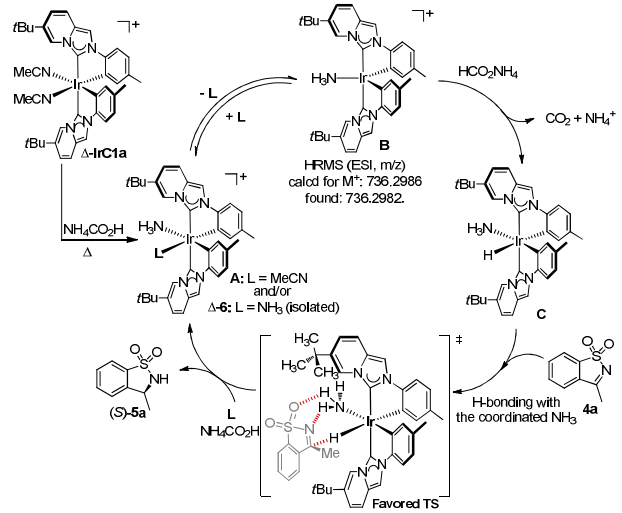
entry	catalyst (mol%)	solvent	T (°C)	t (h)	yield (%)[b]	ee (%)[c]
1	Δ-**IrC1a**(0.5)	THF/H_2O(1:1)	50	6	64	93
2	Δ-**IrC1a**(0.5)	DMF/H_2O(2:1)	50	2.5	93	99
3	Δ-**IrC1a**(0.05)	DMF/H_2O(2:1)	50	11	90	97
4	Δ-**IrC1a**(0.05)	DMF/H_2O(2:1)	60	5	91	98
5	Δ-**IrC1a**(0.02)	DMF/H_2O(2:1)	60	12	84	94
6	Δ-**IrC1a**(0.01)	DMF/H_2O(2:1)	60	17	82	90
7	Δ-**IrC1b**(0.05)	DMF/H_2O(2:1)	60	5	70	92
8	Δ-**IrO**(0.05)	DMF/H_2O(2:1)	60	5	trace	n.d.
9	Δ-**IrS**(0.05)	DMF/H_2O(2:1)	60	5	17	94
10[d]	Δ-**IrC1a**(0.05)	DMF/H_2O(2:1)	60	5	12	15
11[e]	Δ-**IrC1a**(0.05)	DMF/H_2O(2:1)	60	5	94	67
12	Δ-**6**(0.05)	DMF/H_2O(2:1)	60	5	98	94

[a] Reaction conditions: **4a** (0.10 mmol), HCO_2NH_4 (0.90 mmol) as the H source under air atmosphere. [b] Yield determined by ^1H NMR analysis. [c] Ee value determined by chiral HPLC analysis. [d] HCO_2Na as the hydrogen source. [e] HCO_2H/Et_3N (5:2) as the hydrogen source.

Based on the catalytic outcomes and observed potential intermediates, we propose a mechanism (Scheme 2). First, Δ-**IrC1a** undergoes ligand exchange and affords complex **A** or/and Δ-**6** as the active catalyst in the catalytic cycle. Subsequently, **A** or/and Δ-**6** slowly liberate one MeCN or NH_3 and generate the 16-electron

View Article Online
DOI: 10.1039/C7CC04691J

species **B** (observed in HRMS), followed by a fast hydride transfer to produce the highly reactive intermediate **C**. The final transfer of a hydride and a proton to imine **4a** leads to the formation of **5a** and regeneration of the active catalyst. Notably, ammonium formate not only serves as the hydrogen source, but also provides free ammonia to generate the real active catalyst. In addition, water cluster might also be involved considering the strong solvent effects in the catalysis.[25] The excellent asymmetric induction is presumably attributed to the less steric hindrance in the favored transition state in addition to the hydrogen-bonding network (Scheme 2). This mechanism is consistent with an observed *S*-configuration of the product.[22b]



Scheme 2 Tentatively mechanistic proposal.

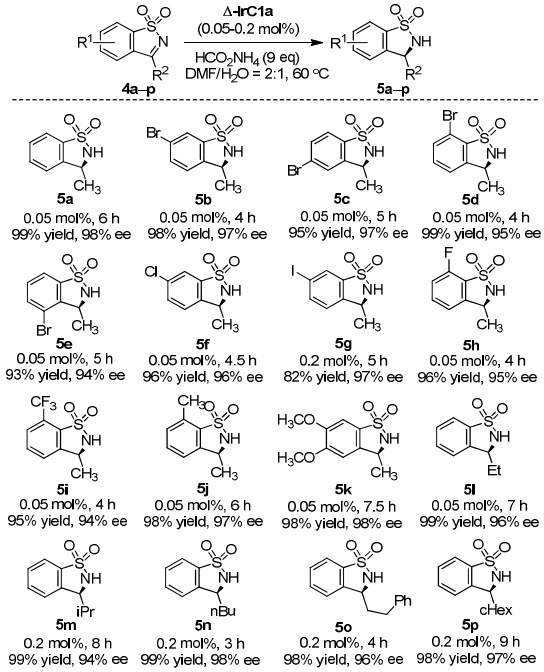


Fig. 2 Substrate Scope. The yield refers to the isolated yield.

Next, a range of cyclic *N*-sulfonylimines bearing electron withdrawing (products **5b–i**) or donating groups (products **5j, k**) within the fused benzene ring, and a steric more demanding aliphatic substitutent on the imine moiety (products **5l–p**) were examined. The desired products were formed in 82–99% yields and with 94–98% ee (Fig. 2). It is worth to mention that all the halogen substituents were well tolerated in the reaction, providing the opportunity for further functionalization of the chiral sultams. Moreover, Fig. 3 reveals that catalyst Δ-**IrC1a** could remarkably discern structural differences between the two aromatic rings in the benzofused *N*-sulfonylimines with a second aryl on the imino moiety, by affording chiral diaryl imines **5q–x** in excellent yields (95–99%) and enantioselectivities (96–98% ee).

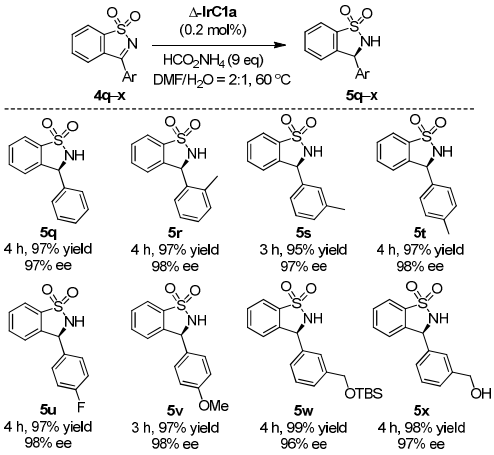
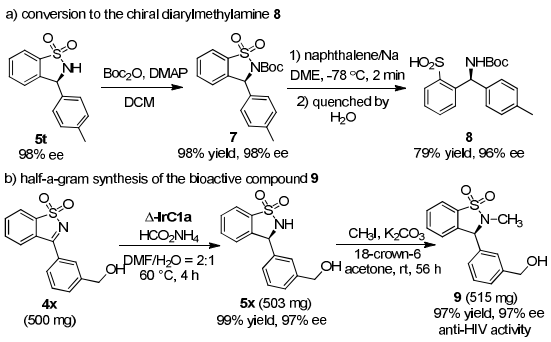


Fig. 3 Substrate Scope. The yield refers to the isolated yield.

Finally, we investigated the synthetic utility of this method. For instance, the ATH product **5t** could be readily converted into the corresponding chiral diarylmethylamine **8** with 96% ee through an *N*-Boc protection followed by fast treatment with naphthalene sodium. Notably, chiral diarylmethylamines are important building blocks in numerous bioactive compounds and very difficult to achieve by enantioselective reduction of imines.[26] Moreover, a half-gram-scale synthesis of bioactive chiral sultam **9** with anti-HIV activity was developed based on the ATH of cyclic *N*-sulfonylimine **4x** and an *N*-methylation step. 515 mg of compound **9** was obtained in a total yield of 96% and with 97% ee (Scheme 3).[22b,27]



Scheme 3 Synthetic utility of the method.

Conclusions

In summary, we have developed a cyclometalating *N*-heterocyclic carbene iridium catalyst Δ-$[Ir(CycloNHC)_2(MeCN)_2]PF_6$ with exclusive metal-centered chirality for enantioselective transfer

View Article Online
DOI: 10.1039/C7CC04691J

hydrogenation of imines. The catalyst exhibits superior performance in the ATH reaction of cyclic *N*-sulfonylimines regarding catalyst loading (down to 0.01 mol%), substrate scope (24 examples) and enantioselectivities (94–98% ee). During the catalytic process, ammonium formate releases free ammonia to generate the real active catalyst in addition to serving as the hydrogen source.We believe that this system will not only provide new considerations of catalyst design for ATH of imines, but also have remarkable potential for application in a practical method to prepare chiral sultams and diarylmethylamines.

Acknowledgements

We gratefully acknowledge funding from the National Natural Science Foundation of China (grant nos. 21572184 and 21472154), the Natural Science Foundation of Fujian Province of China (grant no. 2017J06006), and the Fundamental Research Funds for the Central Universities (grant no. 20720160027).

Notes and references

1 For recent reviews on ATH of imines, see: (*a*) F. Foubelo and M. Yus, *Chem. Rec.*, 2015, **15**, 907; (*b*) H. G. Nedden, A. Zanotti-Gerosa and M. Wills, *Chem. Rec.*, 2016, **16**, 2623.

2 For selected examples of recent work on transition-metal-catalyzed ATH of imines, see: (*a*) W. Zuo, A. J. Lough, Y. F. Li and R. H. Morris, *Science*, 2013, **342**, 1080; (*b*) F. W. Monnard, E. S. Nogueira, T. Heinisch, T. Schirmer and T. R. Ward, *Chem. Sci.* 2013, **4**, 3269; (*c*) V. S. Shende, S. K. Shingote, S. H. Deshpande, N. Kuriakose, K. Vanka and A. A. Kelkar, *RSC Adv.* 2014, **4**, 46351; (*d*) K. Saito, H. Miyashita and T. Akiyama, *Org. Lett.*, 2014, **16**, 5312; (*e*) H. Xu, P. Yang, P. Chuanprasit, H. Hirao and J. Zhou, *Angew. Chem. Int. Ed.*, 2015, **54**, 5112; (*f*) I. Chatterjee, M. Oestreich, *Angew. Chem. Int. Ed.*, 2015, **54**, 1965; (*g*) V. S. Shende, S. H. Deshpande, S. K. Shingote, A. Joseph and A. A. Kelkar, *Org. Lett.*, 2015, **17**, 2878; (*h*) S. Li, G. Li, W. Meng and H. Du, *J. Am. Chem. Soc.*, 2016, **138**, 12956; (*i*) H.-J. Pan, T. W. Ng and Y. Zhao, *Org. Biomol. Chem.*, 2016, **14**, 5490; (*j*) K. Zhang, J. An, Y. Su, J. Zhang, Z. Wang, T. Cheng and G. Liu, *ACS Catal.*, 2016, **6**, 6229; (*k*) R. Bigler and A. Mezzetti, *Org. Proc. Res. Dev.*, 2016, **20**, 253; (*l*) H.-J. Pan, Y. Zhang, C. Shan, Z. Yu, Y. Lan and Y. Zhao, *Angew. Chem. Int. Ed.*, 2016, **55**, 9615.

3 M. J. Stirling, G. Sweeney, K. MacRory, A. J. Blacker and M. I. Page, *Org. Biomol. Chem.*, 2016, **14**, 3614.

4 N. Fleury-Brégeot, V. Fuente, S. Castillón and C. Claver, *ChemCatChem.*, 2010, **2**, 1346.

5 (*a*) S. Gomez, J. A. Peters and T. Maschmeyer, *Adv. Synth. Catal.*, 2002, **344**, 1037; (*b*) V. I. Tararov and A. Börner, *Synlett*, 2005, 203.

6 S. A. Lee, S. H. Kwak and K.-I. Lee, *Chem. Commun.*, 2011, **47**, 2372.

7 H.-U. Blaser and F. Spindler, *Org. React.*, 2009, **74**, 1.

8 A. A. Mikhailine, M. I. Maishan and R. H. Morris, *Org. Lett.*, 2012, **14**, 4638.

9 (*a*) M. Albrecht, R. H. Crabtree, J. Mata and E. Peris, *Chem. Commun.*, 2002, **1**, 32; (*b*) M. Albrecht, J. R. Miecznikowski, A. Samuel, J. W. Faller and R. H. Crabtree, *Organometallics*, 2002, **21**, 3596. (*c*) W. W. O, A. J. Lough and R. H. Morris, *Chem. Commun.*, 2010, **46**, 8240; (*d*) J. DePasquale, M. Kumar, M. Zeller and E. T. Papish, *Organometallics*, 2013, **32**, 966; (*e*) J. Holmes, C. M. Pask and C. E. Willans, *Dalton Trans.*, 2016, **45**, 15818; (*f*) S. Sabater, M. J. Page, M. F. Mahon and M. K. Whittlesey, *Organometallics*, 2017, **36**, 1776; (*g*) A. Azua, M. Finn, H. Yi, A. B. Dantas and A. Voutchkova-Kostal, *ACS Sustainable Chem. Eng.*, 2017, **5**, 3963; (*h*) E. Korytiaková, N. O. Thiel, F. Pape and J. F. Teichert, *Chem. Commun.*, 2017, **53**, 732.

10 For selected examples on ATH of ketones catalyzed by chiral metal carbene complexes, see: (*a*) R. Jiang, X. Sun, W. He and H. Chen, Y. Kuang, *Appl. Organometal. Chem.*, 2009, **23**, 179; (*b*) C. Diez and U. Nagel, *Appl. Organometal. Chem.*, 2010, **24**, 509; (*c*) M. Yoshimura, R. Kamisue and S. Sakaguchi, *J. Orgomet. Chem.*, 2013, **740**, 26; (*d*) S. Sabater, M. Baya and J. A. Mata, *Organometallics*, 2014, **33**, 6830; (*e*) K. Yoshida, T. Kamimura, H. Kuwabara and A. Yanagisawa, *Chem. Commun.*, 2015, **51**, 15442.

11 For representative work on chiral-at-metal Lewis acid catalysis developed by us, see: (*a*) H. Huo, C. Fu, K. Harms and E. Meggers, *J. Am. Chem. Soc.*, 2014, **136**, 2990; (*b*) X. Shen, H. Huo, C. Wang, B. Zhang, K. Harms and E. Meggers, *Chem. Eur. J.*, 2015, **21**, 9720; (*c*) C. Wang, L.-A. Chen, H. Huo, X. Shen, K. Harms, L. Gong and E. Meggers, *Chem. Sci.*, 2015, **6**, 1094; (*d*) Y. Tan, W. Yuan, L. Gong and E. Meggers, *Angew. Chem. Int. Ed.*, 2015, **54**, 13045; (*e*) L. Song, L. Gong and E. Meggers, *Chem. Commun.*, 2016, **52**, 7699; (*f*) C. Tian, L. Gong and E. Meggers, *Chem. Commun.*, 2016, **52**, 4207; (*g*) C. Wang, K. Harms and E. Meggers, *Angew. Chem. Int. Ed.*, 2016, **55**, 13495. For a recent account, see: L. Zhang and E. Meggers, *Acc. Chem. Res.*, 2017, **50**, 320.

12 For recent applications of this class of chiral-at-metal Lewis acid catalysts by other groups, see: (*a*) J. Gong, K. Li, S. Qurban and Q. Kang, *Chin. J. Chem.*, 2016, **34**, 1225; (*b*) G.-Q. Xu, H. Liang, J. Fang, Z.-L. Jia, J.-Q. Chen and P.-F. Xu, *Chem. Asian J.*, 2016, **11**, 3355; (*c*) G.-J. Sun, J. Gong and Q. Kang, *J. Org. Chem.*, 2017, **82**, 796; (*d*) T. Deng, G. K. Thota, Y. Li and Q. Kang, *Org. Chem. Front.*, 2017, **4**, 573; (*e*) S.-W. Li, J. Gong and Q. Kang, *Org. Lett.*, 2017, **19**, 1350.

13 (*a*) Y. Zhu, Y. Fan and K. Burgess, *J. Am. Chem. Soc.,* 2010, **132**, 6249; (*b*) Y. Zhu and K. Burgess, *Acc. Chem. Res.*, 2012, **45**, 1623; (*c*) D. J. Nelson and S. P. Nolan, *Chem. Soc. Rev.*, 2013, **42**, 6723; (*d*) S. C. Vummaleti, D. J. Nelson, A. Poater, A. Gómez-Suárez, D. B. Cordes, A. M. Z. Slawin, S. P. Nolan and L. Cavallo, *Chem. Sci.*, 2015, **6**, 1895; (*e*) A. Gómez-Suárez, D. J. Nelson and S. P. Nolan, *Chem. Commun.*, 2017, **53**, 2650.

14 Y. Zheng, Y. Tan, K. Harms, M. Marsch, R. Riedel, L. Zhang and E. Meggers, *J. Am. Chem. Soc.*, 2017, **139**, 4322.

15 J. R. Miecznikowski and R. H. Crabtree, *Polyhedron*, 2004, 2857.

16 For selected examples of application of chelating NHC ligands in catalysis, see: (*a*) L. Yang, J. Yuan, P. Mao and Q. Guo, *RSC Adv.*, 2015, **5**, 107601; (*b*) G. Tan, S. Enthaler, S. Inoue, B. Blom and M. Driess, *Angew. Chem. Int. Ed.*, 2015, **54**, 2214; (*c*) M. R. Chapman, B. R. M. Lake, C. M. Pask, B. N. Nguyen and C. E. Willans, *Dalton Trans.*, 2015, **44**, 15938; (*d*) K. Farrell, H. Müller-Bunz and M. Albrecht, *Organometallics*, 2015, **34**, 5723; (*e*) D. Ghorai, C. Dutta and J. Choudhury, *ACS Catal.*, 2016, **6**, 709; (*f*) M. D. Miton and P. Garg, *Appl. Organomet. Chem.*, 2016, **30**, 759; (*g*) L. Suntrup, S. Hohloch and B. Sarkar, *Chem. Eur. J.*, 2016, **22**, 18009.

17 C.-H. Chien, S. Fujita, S. Yamoto, T. Hara, T. Yamagata, M. Watanabe and K. Mashima, *Dalton Trans.*, 2008, 916.

18 CCDC 1538578 contains the supplementary crystallographic data for compound *rac*-**IrC1a**. The data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html.

19 M. Helms, Z. Lin, L. Gong, K. Harms and E. Meggers, *Eur. J. Inorg. Chem.*, 2013, 4164.

20 H. Wang, T. Jiang and M.-H. Xu, *J. Am. Chem. Soc.*, 2013, **135**, 971.

21 For selected examples on ATH of cyclic *N*-sulfonylimines, see: (*a*) J. Mao and D. C. Baker, *Org. Lett.*, 1999, **1**, 841; (*b*) Y.-C. Chen, T.-F. Wu, J.-G. Deng, H. Liu, X. Cui, J. Zhu, Y.-Z. Jiang, M. C. K. Choi and A. S. C. Chan, *J. Org. Chem.*, 2002, **67**, 5301; (*c*) P.-N. Liu, P.-M. Gu, J.-G. Deng, Y.-Q. Tu and Y.-P. Ma, *Eur. J. Org. Chem.*, 2005, 3221; (*d*) S. A. Lee, S. H. Kwak and K.-I. Lee, *Chem. Commun.*, 2011, **47**, 2372.

22 For representative studies on asymmetric hydrogenation of cyclic *N*-sulfonylimines, see: (*a*) Y.-Q. Wang, S.-M. Lu, Y.-G. Zhou and *J. Org. Chem.*, 2007, **72**, 3729; (*b*) C.-B. Yu, D.-W. Wang and Y.-G. Zhou, *J. Org. Chem.*, 2009, **74**, 5633; (*c*) F. Chen, Z. Li, Y. He and Q. Fan, *Chin. J. Chem.*, 2010, **28**, 1529.

23 **Δ-IrC1a** also exhibits high catalytic activity for the ATH reaction of other imines, in a primary study, 6,7-dimethoxy-1-methyl-3,4-dihydro-isoquinoline could be quantitatively converted into its corresponding amine derivative with 87% ee at a catalyst loading of 0.5 mol%.

24 D. J. Nelson, B. J. Truscott, J. D. Egbert and S. P. Nolan, *Organometallics*, 2013, **32**, 3769.

25 X. Wu, X. Li, A. Zanotti-Gerosa, A. Pettman, J. Liu, A. J. Mills and J. Xiao, *Chem. Eur. J.*, 2008, **14**, 2209.

26 G. Hou, R. Tao, Y. Sun, X. Zhang and F. Gosselin, *J. Am. Chem. Soc.*, 2010, **132**, 2124.

27 A. Rolfe, K. Young and P. R. Hanson, *Eur. J. Org. Chem.*, 2008, 5254.