DOI: 10.1002/anie.201404305

Chiral-at-Metal Complexes

Asymmetric Catalysis Mediated by the Ligand Sphere of Octahedral Chiral-at-Metal Complexes

*Lei Gong, Liang-An Chen, and Eric Meggers**

asymmetric catalysis · chiral metal centers · coordination modes · homogeneous catalysis

Due to the relationship between structure and function in chemistry, access to novel chemical structures ultimately drives the discovery of novel chemical function. In this light, the formidable utility of the octahedral geometry of six-coordinate metal complexes is founded in its stereochemical complexity combined with the ability to access chemical space that might be unavailable for purely organic compounds. In this Minireview we wish to draw attention to inert octahedral chiral-at-metal complexes as an emerging class of metal-templated asymmetric "organocatalysts" which exploit the globular, rigid nature and stereochemical options of octahedral compounds and promise to provide new opportunities in the field of catalysis.

1. Introduction

Research on asymmetric catalysis is fueled by a growing demand for optically active compounds in the chemical and pharmaceutical industries.[1,2] Herein we review a class of recently discovered asymmetric catalysts, which formally do not belong to any of the main branches of catalysis—biocatalysis, organocatalysis, and transition metal catalysis—namely substitutionally and configurationally inert octahedral chiral-at-metal complexes.[3,4] In these metal-templated asymmetric "organocatalysts", the central transition metal serves as a structural anchor point and provides metal centrochirality, while catalysis is mediated through the organic ligand sphere. A combination of properties render octahedral transition metal complexes powerful templates for the design of asymmetric catalysts: 1) The sophisticated stereochemistry of octahedral metal complexes (up to 30 stereoisomers at a single octahedral stereocenter) permits the generation of complicated structures with manifold opportunities for the tailored arrangement of functional groups for performing multifunctional catalysis. 2) Octahedral stereocenters simplify the design of defined globular, rigid structures because the molecular geometries are basically constructed from a common center with steric crowding and chelating ligands limiting the degree of conformational flexibility; this is not only advantageous for entropic reasons but also facilitates the intuitive and rational catalyst optimization. It is noteworthy that the same features of octahedral metal complexes, namely sophisticated structural opportunities in combination with conformational rigidity, have been proven advantageous for the design of high-affinity and selective DNA binders and enzyme inhibitors.[5,6] This Minireview will focus on reports of metal-templated asymmetric catalysis through the ligand sphere, whereas work in which the chiral metal center serves as a reactive coordination center will not be considered here.[7]

2. Octahedral Templates Containing Chiral Ligands

In order to exploit the structural features of chiral octahedral complexes, the stereochemistry must first be implemented. The required control over the relative and absolute configuration at the metal center probably constitutes the current impediment to the metal-templated approach.[8] A convenient strategy to address this problem employs multidentate chiral organic ligands with the purpose of either directing the formation of metal centrochirality or facilitating the chromatographic separation of the formed mixtures of (enantiomerically pure) diastereomers.

---

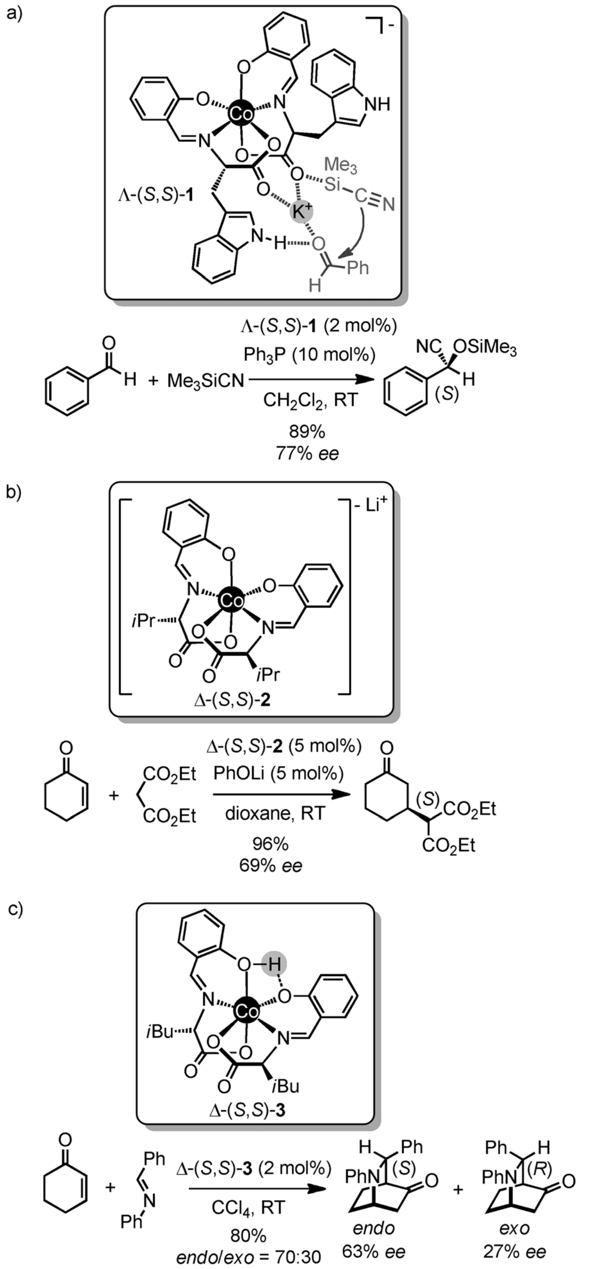
[*] Dr. L. Gong, B.Sc. L.-A. Chen, Prof. Dr. E. Meggers
Key Laboratory for Chemical Biology of Fujian Province
and Department of Chemical Biology
College of Chemistry and Chemical Engineering
Xiamen University, Xiamen 361005 (P.R. China)

Prof. Dr. E. Meggers
Fachbereich Chemie, Philipps-Universität Marburg
Hans-Meerwein-Strasse, 35043 Marburg (Germany)
E-mail: meggers@chemie.uni-marburg.de

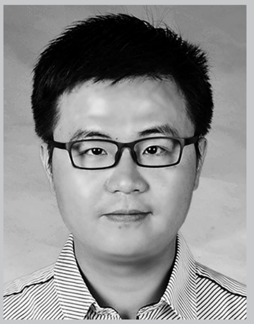
© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

2.1. Cobaltate(III) Schiff Base Complexes

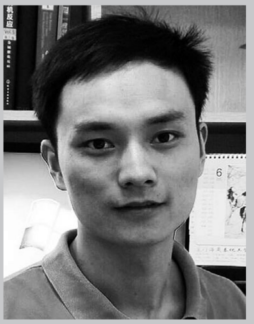
Belokon and co-workers introduced a family of inert chiral cobaltate(III) Schiff base complexes as asymmetric catalysts.[9–12] These complexes combine metal-centered chirality with stereogenic carbons in the coordinating ligands. Two tridentate chiral Schiff base ligands, obtained from the condensation of salicylaldehyde and deprotonated chiral α-amino acids, are octahedrally coordinated to a central cobalt(III) ion, thus forming negatively charged cobaltate(III) complexes. The authors demonstrated that the catalytic properties of these complexes can be tuned by varying the amino acid side chain, the absolute configurations of the involved carbon- and cobalt-based stereocenters, and the nature of the counterion. For example, potassium Λ-bis(*N*-salicylidene-(*S*)-tryptophanato)cobaltate [Λ-(*S*,*S*)-**1**] was reported to be an effective Lewis acid catalyst for asymmetric cyanosilylation (Scheme 1 a).[9] The coordinatively saturated and inert complex was obtained as a mixture of two diastereomers from the reaction of tryptophan with salicylaldehyde and $Na_3[Co(CO_3)_3]$. The formed Λ-(*S*,*S*) and Δ-(*S*,*S*) diastereomers were separated by flash chromatography on Al_2O_3 and subsequent ion-exchange chromatography. It was demonstrated that the Λ-(*S*,*S*) diastereomer of the chiral potassium cobaltate salt [Λ-(*S*,*S*)-**1**] (2 mol %) efficiently catalyzes the asymmetric trimethylsilylcyanation of benzaldehyde at room temperature in the presence of the cocatalyst PPh_3 (10 mol %) in 89 % yield with 77 % *ee*. Notably, the diastereomer Δ-(*S*,*S*)-**1**, bearing the opposite configuration at the cobalt center, did not provide any enantioselectivity, thus demonstrating that the absolute configuration at the metal center is crucial for the asymmetric induction in this reaction. The authors propose a mechanism in which the carboxylate moieties of the cobaltate anion serve as coordinating groups for the potassium ion, which itself functions as a Lewis acid to



Scheme 1. Asymmetric catalysis with chiral cobalt(III) Schiff base complexes.



Lei Gong received his BSc and PhD degrees from Xiamen University (P. R. China) in 2002 and 2008, respectively. Thereafter he moved to the Philipps-University Marburg, Germany where he worked as a postdoctoral fellow with Professor Eric Meggers. Since 2011, Lei Gong has been an Associate Professor at the College of Chemistry and Chemical Engineering at Xiamen University. His research interests include the synthesis of chiral metal complexes and their application in asymmetric catalysis.



Liang-an Chen received his BSc degree in chemistry from Fuyang Teachers College in 2008. He is currently carrying out PhD studies under the direction of Professor Eric Meggers at Xiamen University (P. R. China). His current research interests focus on asymmetric catalysis with chiral-at-metal complexes.

Eric Meggers received his PhD from the University of Basel (Switzerland) under the guidance of Professor Bernd Giese. In 2002, after postdoctoral research with Professor Peter G. Schultz at the Scripps Research Institute in La Jolla (USA), he became an Assistant Professor in the Chemistry Department at the University of Pennsylvania (USA). Since 2007, he has been Professor at the Department of Chemistry of the Philipps-University Marburg (Germany) and currently holds a secondary appointment as Professor at the College of Chemistry and Chemical Engineering of Xiamen University (P. R. China). His research program focuses on the implementation of metal stereochemistry in medicine, chemical biology, and chemical synthesis.

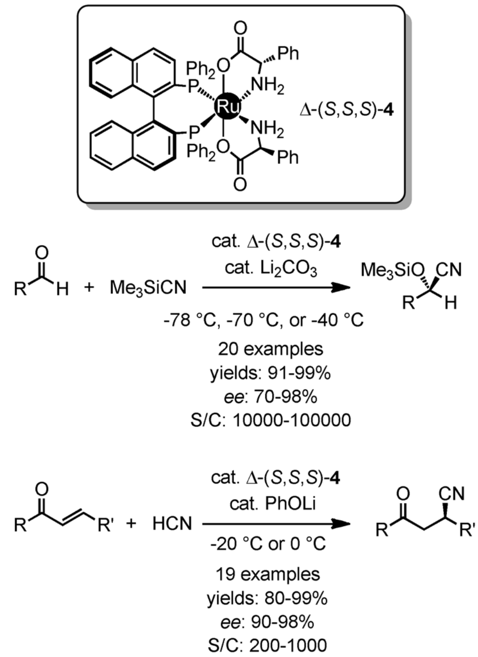
coordinate and activate the benzaldehyde. Further activation of the benzaldehyde can be anticipated from a hydrogen bond between the aldehyde oxygen and an indole NH group. Trimethylsilylcyanide, on the other hand, might be activated and positioned through the interaction of the silicon center with one of the nucleophilic carboxylate groups of the cobaltate anion.

In a related example, the lithium cobaltate complex Δ-(*S*,*S*)-**2**, which differs from Λ-(*S*,*S*)-**1** in terms of the configuration at cobalt (Δ instead of Λ), the amino acid side chain (Val instead of Trp) and the counterion (Li^+ instead of K^+), was reported to catalyze the asymmetric Michael addition of diethyl malonate to 2-cyclohexen-1-one in the presence of the base PhOLi with high yield but only a modest *ee* value of 69% (Scheme 1 b).[10] The importance of the absolute configuration at the metal center became apparent from an experiment with the diastereomer Λ-(*S*,*S*)-**2** which provided only an enantiomeric excess of 4% (*R*-configured product) and a yield of 11%.

Maleev and co-workers extended the use of substitutionally inert cobaltate complexes from asymmetric Lewis acid catalysis to asymmetric Brønsted acid catalysis by replacing the alkali metal counterion with a proton.[13] They recently reported that the complex Δ-(*S*,*S*)-**3**, which is prepared from its lithium salt by using the proton form of an ion-exchange resin, catalyzes an asymmetric aza-Diels–Alder reaction (Scheme 1 c). Accordingly, the reaction of *N*-benzylideneaniline with 2-cyclohexen-1-one in the presence of 2 mol% Δ-(*S*,*S*)-**3** afforded the major *endo* cycloaddition product with 63% *ee*. In this reaction, Δ-(*S*,*S*)-**3** apparently activates the Schiff base by protonation and the asymmetric induction is achieved due to the formation of an intermediate tight ion pair[14] between the formed iminium cation and cobaltate anion in the nonpolar solvent carbon tetrachloride. Interestingly, as with the other discussed cobaltate complexes, the outcome of the catalysis critically depended on the configuration at the metal center, with the diastereomer Λ-(*S*,*S*)-**3** providing an *ee* value of only 6% (opposite enantiomer preferred).

2.2. Ruthenium(II) Binap α-Aminoacidato Complexes

Ohkuma and co-workers reported a highly powerful class of inert, chiral octahedral asymmetric catalysts in which chirality at the metal center is combined with chirality in the ligand sphere.[15–22] In their chiral ruthenium(II) complexes, in addition to chirality at the octahedral ruthenium center, axial chirality is provided by one (*S*)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl [(*S*)-binap], and chirality from asymmetric tetrahedral carbons is derived from two α-aminacidato ligands. In this rather unique system, the ligand-based chiral information not only influences the catalysis by affecting the arrangement of substituents and functional groups at the periphery of the ruthenium complex, but at the same time it directs the diastereoselective, asymmetric implementation of the configuration at the metal center. Accordingly, the reaction of $[RuCl_2\{(S)\text{-binap}\}(N,N\text{-dimethylformamide})]_n$ (oligomeric form) with 3 equivalents of (*S*)-phenylglycine (PhGly) sodium salt in a DMF/CH_3OH solvent mixture afforded the single diastereoisomer Δ-(*S*,*S*,*S*)-**4** in 74% yield, which due to its stability could be purified by regular silica gel chromatography under air (Scheme 2). In the presence of Li_2CO_3, the complex Δ-(*S*,*S*,*S*)-**4** catalyzes the asymmetric cyanosilylation of aldehydes with high enantiomeric excess and impressive substrate-to-catalyst (S/C) ratios of up to 100000.[16] Mass spectrometry and ^{1}H NMR spectroscopy imply that the active catalyst is a bimetallic Ru–Li species which apparently acts as a chiral Lewis acid catalyst. In more recent work, the same complex is demonstrated to be also a highly efficient catalyst for the asymmetric hydrocyanation of α,β-unsaturated ketones in the presence of lithium phenolate (Scheme 2).[19] Notably, no 1,2-addition was observed. Interestingly, the catalyst was so robust that it could be reused several times while maintaining high enantioselectivities. Although catalyst Δ-(*S*,*S*,*S*)-**4** contains in addition to chirality at the octahedral ruthenium center also the axial chirality of the binap ligand and two stereogenic carbon atoms of the coordinated deprotonated amino acids, it can be expected that the metal centrochirality is important for the efficiency of this catalyst.



Scheme 2. Asymmetric cyanosilylation of aldehydes and asymmetric hydrocyanation of α,β-unsaturated ketones with an inert chiral ruthenium(II) complex. S/C = substrate-to-catalyst ratio.

To summarize this section, the unique catalysts developed by Belokon et al., Maleev et al., and Ohkuma et al. demonstrate how an octahedral stereocenter in combination with chirality derived from coordinating ligands can be exploited for the design of asymmetric catalysts in which the metal center has a purely structural role and contributes to the precise arrangement of key functional groups in three-dimensional space.

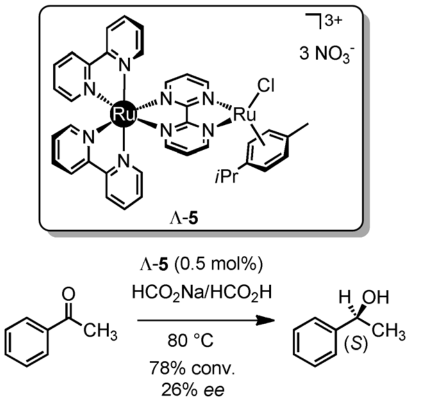
© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

3. Octahedral Templates with Exclusive Metal-Centered Chirality

Octahedral metal complexes which display chirality at the metal center as the sole element of chirality are conceptually appealing since they allow the direct investigation of the scope of chirality transfer from the octahedral centrochirality of the catalyst to the tetrahedral centrochirality typically present in the organic reaction products.[23] Octahedral chiral-only-at-metal complexes are usually derived by the resolution of diastereomic salts using chiral counterions or, in a more recent strategy, by applying chiral auxiliaries.[4,8,24]

3.1. Ruthenium(II) Polypyridyl Complexes

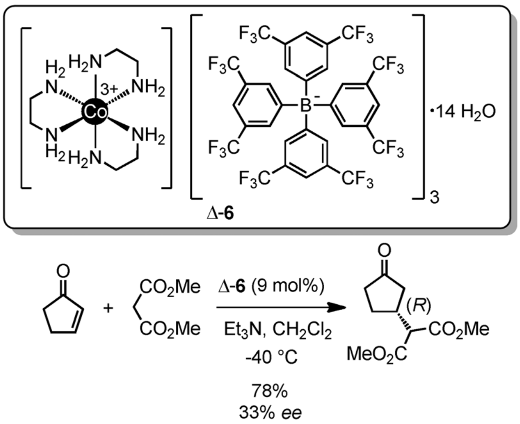
Fontecave and co-workers recently reported the use of an inert octahedral chiral-at-metal complex as a chiral and inert "metalloligand" for a second, catalytic metal center.[25,26] Scheme 3 displays the dinuclear catalyst Λ-**5** in which the chiral-at-metal Λ-[Ru(2,2′-bipyridine)$_2$(2,2′-bipyrimidine)]$^{2+}$ complex serves, through a bridging 2,2′-bipyrimidine, as a chiral bidentate ligand for a second, catalytically active ruthenium complex. Noteworthy, the chirality in this catalyst exclusively relies on the stereogenic octahedral metal center. However, asymmetric transfer hydrogenation of benzophenone with formate and catalyzed by Λ-**5** (0.5 mol %) provided the corresponding alcohol with a low enantioselectivity of 26 % *ee*. Most other tested substrates afforded even lower *ee* values. The low asymmetric induction can be rationalized by the large distance between the chiral and catalytic centers. Nevertheless, this work serves as a proof-of-principle for utilizing octahedral centrochirality in asymmetric catalysis.



Scheme 3. Enantioselective transfer hydrogenation catalyzed by a diruthenium complex in which one ruthenium center has a purely structural role ("metalloligand") and provides the asymmetric induction with its metal-centered chirality.

3.2. Cobalt(III) Ammines

Gladysz and co-workers recently demonstrated that simple chiral-at-metal Werner complexes can serve as enantioselective H-bonding catalysts.[27] For this, enantiopure Δ-[Co(1,2-ethylenediamine)$_3$]$^{3+}$ was rendered soluble in CH_2Cl_2 by using tetrakis[3,5-trifluoromethyl)phenyl]borate (BArF) as the counterion (see Δ-**6** in Scheme 4). Interestingly, the complex Δ-**6**, at a loading of 9 mol %, was capable of catalyzing the Michael addition of dimethyl malonate to 2-cyclopenten-1-one in CH_2Cl_2 in the presence of Et_3N to afford the Michael addition product in 78 % yield, albeit with a low enantioselectivity of just 33 % *ee*. However, as the authors note, since such cobalt(III) Werner cations are substitutionally inert, the asymmetric induction must take place by means of a second-coordination-sphere mechanism, possibly with the participation of hydrogen-bonded water molecules.

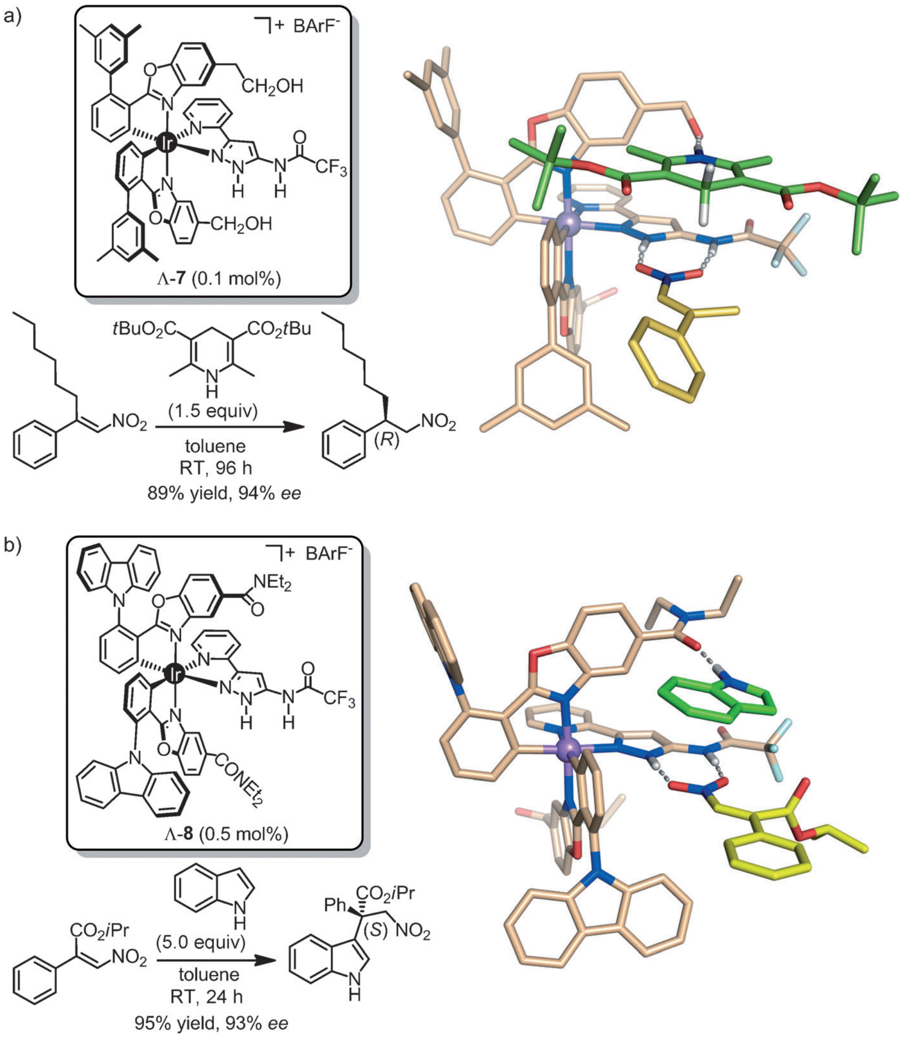


Scheme 4. Enantioselective Michael addition catalyzed by an inert, chiral-at-metal Werner complex.

3.3. Cyclometalated Iridium(III) Complexes

Finally, our group recently introduced bis-cyclometalated iridium(III) complexes as highly effective asymmetric catalysts for the enantioselective conjugate reduction of β,β-disubstituted nitroalkenes with a Hantzsch ester as the reducing agent.[28] For example, the hydrogenation of (*E*)-1-hexyl-2-nitrostyrene with the di-*tert*-butyl Hantzsch ester in toluene at room temperature in the presence of just 0.1 mol % of Λ-**7** provided (*R*)-2-phenyl-1-nitrooctane in 89 % yield and 94 % *ee* (Scheme 5 a). Since the developed iridium complex is substitutionally inert, the observed catalysis must be mediated entirely through the ligand sphere. A proposed model of the ternary complex leading to the transition state of the enantioselective conjugate reduction of nitroalkenes is presented in Scheme 5 a and follows mechanistic considerations derived from related bifunctional thiourea organocatalysts in which all interactions are mediated by hydrogen bonds.[29] Accordingly, the amidopyrazole moiety serves as a double hydrogen-bond donor to the nitro group, thereby increasing the electrophilicity of the nitroalkene. At the same time, one

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim



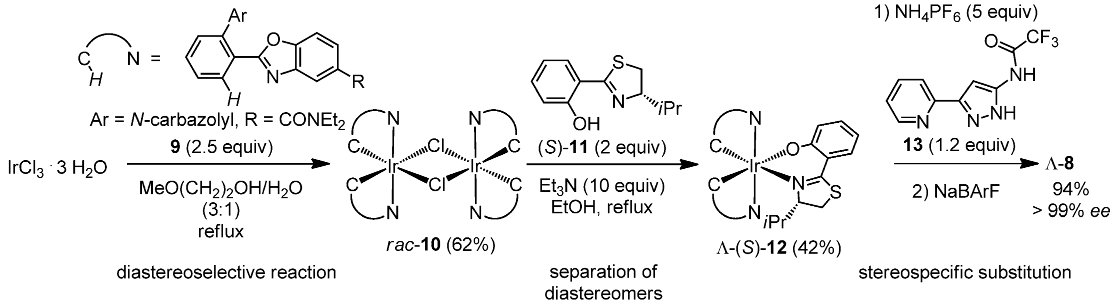
Scheme 5. Inert chiral-at-metal Ir^{III} complexes for asymmetric catalysis. a) Asymmetric transfer hydrogenation with Hantzsch ester. Left: Example of a catalytic reaction with low catalyst loading. Right: Proposed hydrogen-bonded ternary complex consisting of catalyst Λ-**7** (beige), nitroalkene (yellow), and Hantzsch ester (green) leading to the transition state. b) Enantioselective Friedel–Crafts alkylation of indoles with β,β-disubstituted nitroalkenes. Left: Representative example. Right: Proposed hydrogen-bonded ternary complex composed of catalyst Λ-**8** (beige), nitroalkene (yellow), and indole (green) leading to the transition state. Ternary complexes are represented with the PyMOL Molecular Graphics System, Version 1.3 Schrödinger, LLC.

of the two OH groups is in a proper position to accept a hydrogen bond from the NH group of the Hantzsch ester and in that way increases the hydride-donor ability of the Hantzsch ester. The importance of this OH group is demonstrated by a derivative of the catalyst Λ-**7** lacking the two OH groups, which catalyzes the transformation only sluggishly and without any enantioselectivity. It is also interesting to note that the 3,5-dimethylphenyl substituent of the cyclometalated phenylbenzoxazole ligand is very beneficial for the catalysis since it not only improves the asymmetric induction but also increases the turnover frequency by around one order of magnitude. We hypothesize that this effect might be due to a stabilization of the proper hydrogen bonding to the nitroalkene substrate, preventing a dynamic motion perpendicular to the two formed hydrogen bonds. The performance of Λ-**7** is quite remarkable and we estimate that Λ-**7** accelerates the rate of the asymmetric transfer hydrogenation reaction by around 10000-fold, just by orchestrating a number of weak forces with the two substrates. One can speculate that the high rigidity of the octahedral metal complex might provide an advantage over the typically more flexible organocatalysts, considering that the preorganization of the ternary complex must make an important contribution towards lowering the entropic penalty to be paid for the highly organized transition state.[30]

We recently extended the investigation on octahedral chiral-at-metal iridium catalysts to the enantioselective Friedel–Crafts alkylation of indoles with nitroacrylates under the formation of a quaternary all-carbon-substituted stereocenter.[31] To achieve this, Λ-**8** was developed in which we replaced the 3,5-dimethylphenyl group of Λ-**7** by an *N*-carbazolyl moiety, and, most importantly, replaced the hydroxymethyl groups by *N*,*N*-diethylcarboxamides (Scheme 5b). Whereas the reaction of isopropyl (*Z*)-1-phenyl-2-nitroacrylate with indole catalyzed by 5 mol% Λ-**7** afforded the expected conjugate addition product with a modest enantiomeric excess of just 70%, Λ-**8** provided impressive 93% *ee* with merely 0.5 mol% catalyst loading. This performance can be rationalized by the superior hydrogen-bond affinity[32] of the carboxamide over the hydroxy group in combination with the preferred conformation of the amide group, which is rotated out of conjugation with the benzoxazole moiety for steric reasons, thereby placing the amide oxygen in an ideal position for hydrogen bonding with the indole nucleophile. It is noteworthy that tested thiourea organocatalysts only provided very low enantioselectivities for this challenging formation of a quaternary all-carbon-substituted stereocenter.

The developed iridium-based hydrogen-bonding catalysts reach astonishing rate accelerations by three to four orders of magnitude merely by the formation of three hydrogen bonds. Beyond demonstrating the scope of hydrogen-bonding catalysis,[33] this work reveals the power of inert metal complexes as templates for asymmetric organocatalysis. It is important to emphasize that bis-cyclometalated iridium(III) complexes were selected as the metal template of choice as they uniquely enable control over both the relative (orientation of cyclo-

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim



Scheme 6. Synthesis of the enantiomerically pure catalyst Λ-**8**.

metalating ligands) and absolute (Λ versus Δ) configuration at the metal center.[34] The exemplary synthesis of catalysts Λ-**8** is shown in Scheme 6.[31] Accordingly, the reaction of $IrCl_3{\cdot}3H_2O$ with the cyclometalating phenylbenzoxazole ligand **9** affords the racemic dimer complex *rac*-**10** (62%) in a diastereoselective fashion. Reaction of *rac*-**10** with the chiral auxiliary (*S*)-4-isopropyl-2-(2′-hydroxyphenyl)-2-thiazoline [(*S*)-**11**] yields two diastereomeric complexes, of which the faster eluting diastereomer Λ-(*S*)-**12** can be isolated with high purity in a yield of 42% by standard silica gel chromatography. In the last step, Λ-(*S*)-**12** is converted to virtually enantiopure Λ-**8** (> 99% *ee*) in high yields (94%) through the stereospecific substitution of the chiral auxiliary ligand with the pyrazole ligand **13** upon protonation by NH_4PF_6 and subsequent introduction of the BArF counterion. This synthesis thus provides controlled access to single enantiomers of bis-cyclometalated iridium(III) complexes, such as Λ-**7** and Λ-**8**, out of overall eight possible stereoisomers (four diastereomers as pairs of enantiomers). Such organoiridium complexes thereby offer many possibilities for the defined presentation of multiple functional groups within the ligand sphere of the metal complex template—an absolute prerequisite for designing high-performance catalysts. Furthermore bis-cyclometalated iridium(III) complexes have the desired feature that they are substitutionally and configurationally inert, which can be illustrated by the fact that Λ-**8** can be recycled multiple times without significant loss of catalytic performance.[31]

4. Conclusions

We have provided an overview of inert octahedral transition-metal complexes as chiral templates for asymmetric catalysis, in which the transition metal serves as a structural center, whereas catalysis is mediated through the organic ligand sphere. Some of the complexes reported here permit astonishingly low catalyst/substrate ratios, thereby exceeding the performance of most asymmetric organocatalysts and reaching the realm of high-performance (reactive) transition metal catalysis. These examples hint towards an advantage of structurally complicated, rigid metal-based scaffolds over the typical more flexible organocatalysts for noncovalent and noncoordination catalysis, since the defined preorganization of the catalyst together with substrate and reagent in a weakly associated complex must play an important contribution in lowering the entropic penalty to be paid for the highly organized transition state. However, future research will reveal whether the reduced flexibility of metal-templated catalysts presents drawbacks with respect to substrate and reaction scope, and catalytic mechanisms in which conformational changes occur. Nevertheless, the most serious current constraint of octahedral templates lies in limited synthetic strategies for the stereocontrolled synthesis of defined transition metal stereoisomers. Currently the types of usable octahedral templates are restricted to complexes with high symmetry, complexes with a particularly well-chosen combination of chiral ligands, and bis-cyclometalated iridium complexes. Thus, more and diverse metal scaffolds need to be accessible in a stereochemically defined and economical fashion. Finally, besides the design of high-performance metal-templated organocatalysts, it can be envisioned that structural properties of the central metal will be combined with redox and/or photochemical properties of the metal complexes to open new and exciting avenues in asymmetric catalysis.

Funding from the National Natural Science Foundation of P. R. China (21272192, 21201143), the Program for Changjiang Scholars and Innovative Research Team of the Ministry of Education of P. R. China (PCSIRT), the National Thousand Plan Foundation of P. R. China, the 985 Program of the Chemistry and Chemical Engineering disciplines of Xiamen University, and the German Research Foundation (ME1805/4-1) is highly appreciated.

Received: April 15, 2014
Published online: August 25, 2014

---

[1] M. Breuer, K. Ditrich, T. Habicher, B. Hauer, M. Keßeler, R. Stürmer, T. Zelinski, *Angew. Chem.* **2004**, *116*, 806–843; *Angew. Chem. Int. Ed.* **2004**, *43*, 788–824.

[2] For example, of the 25 small-molecule drugs approved by the U.S. Food and Drug Administration (FDA) in 2013, 14 are single enantiomers. See: A. Mullard, *Nat. Rev. Drug Discovery* **2014**, *13*, 85–89.

[3] Previous review: M. Fontecave, O. Hamelin, S. Ménage, *Top. Organomet. Chem.* **2005**, *15*, 271–288.

[4] For the use of octahedral chirality with configurationally stable hexacoordinated phosphate anions, see: a) J. Lacour, D. Linder,

Chem. Rec. **2007**, *7*, 275–285; b) J. Lacour, D. Moraleda, *Chem. Commun.* **2009**, 7073–7089.

[5] B. M. Zeglis, V. C. Pierre, J. K. Barton, *Chem. Commun.* **2007**, 4565–4579.

[6] M. Dörr, E. Meggers, *Curr. Opin. Chem. Biol.* **2014**, *19*, 76–81.

[7] For recent reviews covering labile chiral-at-metal complexes and their catalytic applications, see: a) E. B. Bauer, *Chem. Soc. Rev.* **2012**, *41*, 3153–3167; b) P. Knight, P. Scott, *Coord. Chem. Rev.* **2003**, *242*, 125–143; c) C. Ganter, *Chem. Soc. Rev.* **2003**, *32*, 130–138; d) H. Brunner, *Angew. Chem.* **1999**, *111*, 1248–1263; *Angew. Chem. Int. Ed.* **1999**, *38*, 1194–1208.

[8] For reviews on asymmetric coordination chemistry, see: a) U. Knof, A. von Zelewsky, *Angew. Chem.* **1999**, *111*, 312–333; *Angew. Chem. Int. Ed.* **1999**, *38*, 302–322; b) H. Amouri, M. Gruselle, *Chirality in Transition Metal Chemistry*, Wiley, Chichester, UK, **2008**; c) J. Crassous, *Chem. Soc. Rev.* **2009**, *38*, 830–845; d) E. Meggers, *Eur. J. Inorg. Chem.* **2011**, 2911–2926; e) J. Crassous, *Chem. Commun.* **2012**, *48*, 9684–9692; f) E. C. Constable, *Chem. Soc. Rev.* **2013**, *42*, 1637–1651.

[9] a) Y. N. Belokon, A. G. Bulychev, V. I. Maleev, M. North, I. L. Malfanov, N. S. Ikonnikov, *Mendeleev Commun.* **2004**, *14*, 249–250; b) Y. N. Belokon, V. I. Maleev, I. L. Mal'fanov, T. F. Savel'eva, N. S. Ikonnikov, A. G. Bulychev, D. L. Usanov, D. A. Kataev, M. North, *Russ. Chem. Bull. Int. Ed.* **2006**, *55*, 821–827; c) Y. N. Belokon, V. I. Maleev, D. A. Kataev, I. L. Mal'fanov, A. G. Bulychev, M. A. Moskalenko, T. F. Saveleva, T. V. Skrupskaya, K. A. Lyssenko, I. A. Godovikov, M. North, *Tetrahedron: Asymmetry* **2008**, *19*, 822–831.

[10] Y. N. Belokon, V. I. Maleev, D. A. Kataev, T. F. Saveleva, T. V. Skrupskaya, Y. V. Nelyubina, M. North, *Tetrahedron: Asymmetry* **2009**, *20*, 1746–1752.

[11] Y. N. Belokon, V. I. Maleev, M. North, V. A. Larionov, T. F. Savel'yeva, A. Nijland, Y. V. Nelyubina, *ACS Catal.* **2013**, *3*, 1951–1955.

[12] V. I. Maleev, M. North, V. A. Larionov, I. V. Fedyanin, T. F. Savel'yeva, M. A. Moscalenko, A. F. Smolyakov, Y. N. Belokon, *Adv. Synth. Catal.* **2014**, *356*, 1803–1810.

[13] V. I. Maleev, T. V. Skrupskaya, L. V. Yashkina, A. F. Mkrtchyan, A. S. Saghyan, M. M. Il'in, D. A. Chusov, *Tetrahedron: Asymmetry* **2013**, *24*, 178–183.

[14] For reviews on asymmetric counteranion-directed catalysis, see: a) M. Mahlau, B. List, *Angew. Chem.* **2013**, *125*, 540–556; *Angew. Chem. Int. Ed.* **2013**, *52*, 518–533; b) R. J. Phipps, G. L. Hamilton, F. D. Toste, *Nat. Chem.* **2012**, *4*, 603–614.

[15] T. Ohkuma, N. Kurono, *Synlett* **2012**, 1865–1881.

[16] N. Kurono, K. Arai, M. Uemura, T. Ohkuma, *Angew. Chem.* **2008**, *120*, 6745–6748; *Angew. Chem. Int. Ed.* **2008**, *47*, 6643–6646.

[17] N. Kurono, M. Uemura, T. Ohkuma, *Eur. J. Org. Chem.* **2010**, 1455–1459.

[18] N. Kurono, T. Yoshikawa, M. Yamasaki, T. Ohkuma, *Org. Lett.* **2011**, *13*, 1254–1257.

[19] N. Kurono, N. Nii, Y. Sakaguchi, M. Uemura, T. Ohkuma, *Angew. Chem.* **2011**, *123*, 5655–5658; *Angew. Chem. Int. Ed.* **2011**, *50*, 5541–5544.

[20] M. Uemura, N. Kurono, T. Ohkuma, *Org. Lett.* **2012**, *14*, 882–885.

[21] M. Uemura, N. Kurono, Y. Sakai, T. Ohkuma, *Adv. Synth. Catal.* **2012**, *354*, 2023–2030.

[22] Y. Sakaguchi, N. Kurono, K. Yamauchi, T. Ohkuma, *Org. Lett.* **2014**, *16*, 808–811.

[23] For octahedral chiral-at-metal complexes as inducers of asymmetric autocatalysis, see: a) I. Sato, K. Kadowaki, Y. Ohgo, K. Soai, H. Ogino, *Chem. Commun.* **2001**, 1022–1023; b) T. Kawasaki, T. Omine, M. Sato, Y. Morishita, K. Soai, *Chem. Lett.* **2007**, *36*, 30–31.

[24] a) E. Meggers, *Chem. Eur. J.* **2010**, *16*, 752–758; b) L. Gong, M. Wenzel, E. Meggers, *Acc. Chem. Res.* **2013**, *46*, 2635–2644.

[25] O. Hamelin, M. Rimboud, J. Pécaut, M. Fontecave, *Inorg. Chem.* **2007**, *46*, 5354–5360.

[26] For pioneering work on chiral-at-metal octahedral ruthenium(II) complexes with achiral ligands, see also: M. Chavarot, S. Ménage, O. Hamelin, F. Charnay, J. Pécaut, M. Fontecave, *Inorg. Chem.* **2003**, *42*, 4810–4816.

[27] C. Ganzmann, J. A. Gladysz, *Chem. Eur. J.* **2008**, *14*, 5397–5400.

[28] L.-A. Chen, W. Xu, B. Huang, J. Ma, L. Wang, J. Xi, K. Harms, L. Gong, E. Meggers, *J. Am. Chem. Soc.* **2013**, *135*, 10598–10601.

[29] For racemic and enantioselective organocatalytic transfer hydrogenation of nitroalkenes, see: a) Z. Zhang, P. R. Schreiner, *Synthesis* **2007**, 2559–2564; b) N. J. A. Martin, L. Ozores, B. List, *J. Am. Chem. Soc.* **2007**, *129*, 8976–8977; c) N. J. A. Martin, X. Cheng, B. List, *J. Am. Chem. Soc.* **2008**, *130*, 13862–13863; d) J. F. Schneider, M. B. Lauber, V. Muhr, D. Kratzer, J. Paradies, *Org. Biomol. Chem.* **2011**, *9*, 4323–4327.

[30] R. R. Knowles, E. N. Jacobsen, *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 20678–20685.

[31] L.-A. Chen, X. Tang, J. Xi, W. Xu, L. Gong, E. Meggers, *Angew. Chem.* **2013**, *125*, 14271–14275; *Angew. Chem. Int. Ed.* **2013**, *52*, 14021–14025.

[32] Hydrogen-bond basicity and affinity scales reveal that *N*,*N*-dialkylcarboxamides are significantly stronger hydrogen-bond acceptors than alcohols. See: a) C. Laurence, K. A. Brameld, J. Graton, J.-Y. Le Questel, E. Renault, *J. Med. Chem.* **2009**, *52*, 4073–4086; b) C. Laurence, J. Graton, M. Berthelot, F. Besseau, J.-Y. Le Questel, M. Luçon, C. Ouvrard, A. Planchat, E. Renault, *J. Org. Chem.* **2010**, *75*, 4105–4123.

[33] For leading reviews on hydrogen-bonding catalysis, see: a) P. R. Schreiner, *Chem. Soc. Rev.* **2003**, *32*, 289–296; b) Y. Takemoto, *Org. Biomol. Chem.* **2005**, *3*, 4299–4306; c) M. S. Taylor, E. N. Jacobsen, *Angew. Chem.* **2006**, *118*, 1550–1573; *Angew. Chem. Int. Ed.* **2006**, *45*, 1520–1543; d) S. J. Connon, *Chem. Eur. J.* **2006**, *12*, 5418–5427; e) A. G. Doyle, E. N. Jacobsen, *Chem. Rev.* **2007**, *107*, 5713–5743; f) X. Yu, W. Wang, *Chem. Asian J.* **2008**, *3*, 516–532; g) Z. Zhang, P. R. Schreiner, *Chem. Soc. Rev.* **2009**, *38*, 1187–1198.

[34] M. Helms, Z. Lin, L. Gong, K. Harms, E. Meggers, *Eur. J. Inorg. Chem.* **2013**, 4164–4172.

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim