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Expanding the family of bis-cyclometalated chiral-at-metal rhodium(III) catalysts with a benzothiazole derivative†

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Synthetic access to previously elusive single enantiomers of an octahedral chiral-at-metal rhodium(III) complex containing two cyclometalated 2-phenylbenzothiazoles and two acetonitrile ligands is reported. The complex is a superior chiral Lewis acid catalyst compared to its benzoxazole congener which can be rationalized with a higher steric congestion around the coordination sites.

Chiral Lewis acids play an important role in asymmetric catalysis because many reactions are amenable to Lewis acid activation.¹ Recently, we introduced a new class of chiral Lewis acids based on octahedral iridium(III)^{2–7} and rhodium(III)^{8–11} complexes which draw their chirality exclusively from the metal-centered chirality (metal centrochirality).^{12,13} These chiral-only-at-metal complexes are cyclometalated by two 5-*tert*-butyl-2-phenylbenzoxazoles or the analogous benzothiazole ligands in addition to two exchange-labile acetonitriles, which generates a C₂-symmetric, propeller-type geometry.

Whereas the iridium complexes Λ/Δ -IrO and Λ/Δ -IrS have been demonstrated to be excellent catalysts for visible light induced photoredox reactions,^{3,4,6,7} the rhodium congener Λ/Δ -RhO features advantages for regular Lewis acid catalysis,^{8–10} apparently due to a more rapid ligand exchange kinetics (Table 1). We expected that the related complex Λ/Δ -RhS, in which the coordinating benzoxazole moieties are replaced by benzothiazoles, should provide a higher asymmetric induction due to an increased bond length of C–S over C–O which will position the two *tert*-butyl groups somewhat closer to the substrate coordination site. Here we disclose the previously elusive access to the enantiomerically pure benzothiazole complexes Λ - and Δ -RhS, characterize their structures and configurational

Table 1 Overview of bis-cyclometalated, chiral-only-at-metal iridium and rhodium catalysts^a

Entry	Complex	M	X	Remarks
1	Λ - and Δ -IrO	Ir	O	Ref. 2 and 4
2	Λ - and Δ -IrS	Ir	S	Ref. 3 and 5–7
3	Λ - and Δ -RhO	Rh	O	Ref. 8–11
4	Λ - and Δ -RhS	Rh	S	This study

^a Synthesis by an auxiliary-mediated strategy.

stability, and demonstrate their excellent performance as asymmetric catalysts.

The auxiliary-mediated synthesis^{14–18} starts with rhodium trichloride hydrate which is first converted into *rac*-RhS in a yield of 73% by reaction with 2 equiv. of 5-*tert*-butyl-2-phenylbenzothiazole (**1**), followed by a treatment with 1.2 equiv. of AgPF₆ in MeCN (Fig. 1). The complex *rac*-RhS is then reacted with the monofluorinated salicyloxazoline (**S**)-2¹⁹ to provide a diastereomeric mixture of Λ -(**S**)-3 and Δ -(**S**)-3 which can be resolved into pure diastereomers (46% each) based on their different solubilities in EtOH or by silica gel chromatography, or a combination thereof depending on the reaction scale. Configurations were assigned based on the crystal structure of Λ -(**S**)-3 as shown in Fig. 2. Finally, starting with Λ -(**S**)-3 and Δ -(**S**)-3, an acid induced replacement of the coordinated auxiliary ligand with two acetonitriles under retention of the configuration affords the individual enantiomers Λ -RhS (85%) and Δ -RhS (80%). The key aspect of this auxiliary-mediated synthesis is the fluorinated auxiliary (**S**)-2 which was first

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Fig. 1 Auxiliary-mediated synthesis of Λ - and Δ -RhS.

Fig. 2 Crystal structure of the auxiliary complex Λ -(S)-3. ORTEP drawing with 50% thermal ellipsoids. CCDC number 1455732.

introduced by Ceroni and co-workers.¹⁹ All other tested auxiliaries did not provide intermediate rhodium auxiliary complexes with distinct solubilities and were not stable enough for a resolution *via* silica gel chromatography.

The CD spectra of the complexes Λ - and Δ -RhS are shown in Fig. 3, and confirm their mirror-imaged structures. HPLC performed on a chiral stationary phase validates the high enantiomeric purity of the individual enantiomers (Fig. 4).²⁰ For the Δ -enantiomer an er of 99.9 : 0.1 was determined, while peak tailing prevents an accurate validation of the Λ -enantiomer and an er of >99 : 1 was estimated.

Fig. 5 shows the superimposed crystal structures of Λ -RhS and mirror-imaged Δ -RhO, not only confirming the assigned metal-centered configuration of Λ -RhS, but also revealing the differences in how the two *tert*-butyl groups flank the coordination site around the two exchange-labile acetonitrile ligands. In comparison with RhO, the *tert*-butyl groups of RhS are in closer proximity to the labile acetonitriles as quantified by a 0.9 Å shorter intramolecular distance between the quaternary carbons of the two *tert*-butyl groups in RhS (10.5 Å) over RhO (11.4 Å). This is consistent and analogous with a comparison of the related benzoxazole and benzothiazole iridium complexes.^{3,5}

The increased steric hindrance provided by the two *tert*-butyl groups should make RhS an improved asymmetric catalyst for many applications. This is confirmed by the preliminary results shown in Fig. 6. In both enantioselective Michael addition⁸ and a photoinduced enantioselective radical reaction,¹¹ the determined enantioselectivities are appreciably

Fig. 3 CD spectra of Λ - and Δ -RhS recorded in $\text{CH}_3\text{OH} : \text{CH}_2\text{Cl}_2$ 4 : 1.

Fig. 4 HPLC traces of racemic, Λ - and Δ -RhS. HPLC conditions: Daicel CHIRALPAK IB, 250 $\times$ 4.6 mm, column temp. = 25 °C, λ_{abs} = 254 nm, flow rate = 0.6 mL min⁻¹, solvent A = 0.1% aqueous TFA, solvent B = MeCN, gradient = 40% to 50% B in 180 min.

Fig. 5 Superimposed crystal structure of Λ -RhS (grey) with inverted Δ -RhO (green). Fitted is the central metal together with the metal-bound atoms. Atoms are displayed as 50% thermal ellipsoids. CCDC number 1455731 (Λ -RhS).

Fig. 6 Comparison of catalytic performances of Λ -RhS and Δ -RhO.

higher for the benzothiazole (**RhS**) over the benzoxazole (**RhO**) catalyst.²¹

In conclusion, here we reported a new chiral-at-metal benzothiazole complex Λ/Δ -**RhS** which expands the family of bis-cyclometalated rhodium(III) complexes for applications in asymmetric catalysis. Compared to the previously reported benzoxazole complex Λ/Δ -**RhO**, the benzothiazole ligands in Λ/Δ -**RhS** provide a higher steric congestion around the labile acetonitrile ligands, thereby making Λ/Δ -**RhS** a superior asymmetric catalyst. Applications of the new chiral Lewis acid catalyst to challenging asymmetric transformations are underway in our laboratory.

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Notes and references

- Reviews and accounts on different aspects of chiral Lewis acid catalysis: (a) K. Narasaka, *Synthesis*, 1991, 1–11; (b) S. Saito and H. Yamamoto, *Chem. Commun.*, 1997,

- 1585–1592; (c) K. A. Jørgensen, M. Johannsen, S. Yao, H. Audrain and J. Thorhauge, *Acc. Chem. Res.*, 1999, **32**, 605–613; (d) J. S. Johnson and D. A. Evans, *Acc. Chem. Res.*, 2000, **33**, 325–335; (e) G. Desimoni, G. Faita and K. A. Jørgensen, *Chem. Rev.*, 2006, **106**, 3561–3651; (f) S. Kobayashi and C. Ogawa, *Chem. – Eur. J.*, 2006, **12**, 5954–5960; (g) S. Kanemasa, M. Hasegawa and F. Ono, *Chem. Rev.*, 2007, **7**, 137–149; (h) J. Christoffers, G. Korpelly, A. Rosiak and M. Rössle, *Synthesis*, 2007, 1279–1300; (i) M. North, D. L. Usanov and C. Young, *Chem. Rev.*, 2008, **108**, 5146–5226; (j) P. Li and H. Yamamoto, *Top. Organomet. Chem.*, 2011, **37**, 161–183; (k) J. Zhou and Y. Tang, *Top. Organomet. Chem.*, 2011, **36**, 287–312; (l) L. C. Dias, E. C. de Lucca Jr., M. A. B. Ferreira and E. C. Polo, *J. Braz. Chem. Soc.*, 2012, **23**, 2137–2158; (m) H. Yamamoto, *Top. Organomet. Chem.*, 2013, **44**, 315–334.
- 2 H. Huo, C. Fu, K. Harms and E. Meggers, *J. Am. Chem. Soc.*, 2014, **136**, 2990–2993.
- 3 H. Huo, X. Shen, C. Wang, L. Zhang, P. Röse, L.-A. Chen, K. Harms, M. Marsch, G. Hilt and E. Meggers, *Nature*, 2014, **515**, 100–103.
- 4 C. Wang, Y. Zheng, H. Huo, P. Röse, L. Zhang, K. Harms, G. Hilt and E. Meggers, *Chem. – Eur. J.*, 2015, **21**, 7355–7359.
- 5 X. Shen, H. Huo, C. Wang, B. Zhang, K. Harms and E. Meggers, *Chem. – Eur. J.*, 2015, **21**, 9720–9726.
- 6 H. Huo, C. Wang, K. Harms and E. Meggers, *J. Am. Chem. Soc.*, 2015, **137**, 9551–9554.
- 7 C. Wang, J. Qin, X. Shen, R. Riedel, K. Harms and E. Meggers, *Angew. Chem., Int. Ed.*, 2016, **55**, 685–688.
- 8 C. Wang, L.-A. Chen, H. Huo, X. Shen, K. Harms, L. Gong and E. Meggers, *Chem. Sci.*, 2015, **6**, 1094–1100.
- 9 Y. Huang, L. Song, L. Gong and E. Meggers, *Chem. – Asian J.*, 2015, **10**, 2738–2743.
- 10 Y. Tan, W. Yuan, L. Gong and E. Meggers, *Angew. Chem., Int. Ed.*, 2015, **54**, 13045–13048.
- 11 X. Shen, K. Harms, M. Marsch and E. Meggers, submitted for publication.
- 12 For reviews on different aspects of metal-centered chirality, see: (a) J.-L. Pierre, *Coord. Chem. Rev.*, 1998, **178–180**, 1183–1192; (b) U. Knof and A. von Zelewsky, *Angew. Chem., Int. Ed.*, 1999, **38**, 302–322; (c) P. D. Knight and P. Scott, *Coord. Chem. Rev.*, 2003, **242**, 125–143; (d) H. Amouri and M. Gruselle, *Chirality in Transition Metal Chemistry*, Wiley, Chichester, UK, 2008; (e) E. Meggers, *Eur. J. Inorg. Chem.*, 2011, 2911–2926; (f) J. Crassous, *Chem. Commun.*, 2012, **48**, 9684–9692; (g) E. C. Constable, *Chem. Soc. Rev.*, 2013, **42**, 1637–1651; (h) A. von Zelewsky, *Chimia*, 2014, **68**, 297–298.
- 13 For reviews covering chiral-at-metal complexes in catalysis, see: (a) H. Brunner, *Angew. Chem., Int. Ed.*, 1999, **38**, 1194–1208; (b) M. Fontecave, O. Hamelin and S. Ménage, *Top. Organomet. Chem.*, 2005, **15**, 271–288; (c) E. B. Bauer, *Chem. Soc. Rev.*, 2012, **41**, 3153–3167; (d) L. Gong, L.-A. Chen and E. Meggers, *Angew. Chem., Int. Ed.*, 2014, **53**, 10868–10874; (e) Z.-Y. Cao, W. D. G. Brittain, J. S. Fossey and F. Zhou, *Catal. Sci. Technol.*, 2015, **5**, 3441–3451.

- 14 E. Meggers, *Chem. – Eur. J.*, 2010, **16**, 752–758.
- 15 L. Gong, M. Wenzel and E. Meggers, *Acc. Chem. Res.*, 2013, **46**, 2635–2644.
- 16 M. Helms, Z. Lin, L. Gong, K. Harms and E. Meggers, *Eur. J. Inorg. Chem.*, 2013, 4164–4172.
- 17 L.-A. Chen, W. Xu, B. Huang, J. Ma, L. Wang, J. Xi, K. Harms, L. Gong and E. Meggers, *J. Am. Chem. Soc.*, 2013, **135**, 10598–10601.
- 18 For related studies from other groups on auxiliary mediated synthesis of chiral, non-racemic metal complexes, see: (a) C. F. Liu, N. C. Liu and J. C. Bailar, *Inorg. Chem.*, 1964, **3**, 1085–1087; (b) U. Koelle, K. Bücken and U. Englert, *Organometallics*, 1996, **15**, 1376–1383; (c) D. Heseck, Y. Inoue, S. R. L. Everitt, H. Ishida, M. Kunieda and M. G. B. Drew, *Chem. Commun.*, 1999, 403–404; (d) D. Heseck, Y. Inoue, H. Ishida, S. R. L. Everitt and M. G. B. Drew, *Tetrahedron Lett.*, 2000, **41**, 2617–2620; (e) D. Heseck, Y. Inoue, S. R. L. Everitt, H. Ishida, M. Kunieda and M. G. B. Drew, *Inorg. Chem.*, 2000, **39**, 317–324; (f) F. Pezet, J.-C. Daran, I. Sasaki, H. Aït-Haddou and G. G. A. Balavoine, *Organometallics*, 2000, **19**, 4008–4015; (g) O. Chepelin, J. Ujma, X. Wu, A. M. Z. Slawin, M. B. Pitak, S. J. Coles, J. Michel, A. C. Jones, P. E. Barran and P. J. Lusby, *J. Am. Chem. Soc.*, 2012, **134**, 19334–19337; (h) D. L. Davies, K. Singh, S. Singh and B. Villa-Marcos, *Chem. Commun.*, 2013, **49**, 6546–6548.
- 19 E. Marchi, R. Sinisi, G. Bergamini, M. Tragni, M. Monari, M. Bandini and P. Ceroni, *Chem. – Eur. J.*, 2012, **18**, 8765–8773.
- 20 For other reports on non-racemic, chiral-at-metal octahedral rhodium(III) complexes, see: (a) A. H. Krotz, L. Y. Kuo, T. P. Shields and J. K. Barton, *J. Am. Chem. Soc.*, 1993, **115**, 3877–3882; (b) A. Sitlani, C. M. Dupureur and J. K. Barton, *J. Am. Chem. Soc.*, 1993, **115**, 12589–12590; (c) L. Ghizdavu, B. Kolp, A. von Zelewsky and H. Stoeckli-Evans, *Eur. J. Inorg. Chem.*, 1999, 1271–1279; (d) L. Ghizdavu, A. von Zelewsky and H. Stoeckli-Evans, *Eur. J. Inorg. Chem.*, 2001, 993–1003; (e) L. Ghizdavu, O. Lentzen, S. Schumm, A. Brodkorb, C. Moucheron and A. Kirsch-De Mesmaeker, *Inorg. Chem.*, 2003, **42**, 1935–1944; (f) N. Yoshinari and T. Konno, *Inorg. Chem.*, 2008, **47**, 7450–7452; (g) A. Damas, J. Moussa, M. N. Rager and H. Amouri, *Chirality*, 2010, **22**, 889–895; (h) S. Mollin, S. Blanck, K. Harms and E. Meggers, *Inorg. Chim. Acta*, 2012, **393**, 261–268; (i) S. Mollin, R. Riedel, K. Harms and E. Meggers, *J. Inorg. Biochem.*, 2015, **148**, 11–21; (j) R. Rajaratnam, E. K. Martin, M. Dörr, K. Harms, A. Casini and E. Meggers, *Inorg. Chem.*, 2015, **54**, 8111–8120.
- 21 For asymmetric catalysis with octahedral rhodium(III) complexes, see also: (a) H. Nishiyama, H. Sakaguchi, T. Nakamura, M. Horihata, M. Kondo and K. Itoh, *Organometallics*, 1989, **8**, 846–848; (b) Y. Motoyama, H. Narusawa and H. Nishiyama, *Chem. Commun.*, 1999, 131–132; (c) D. Cuervo, M. P. Gamasa and J. Gimeno, *J. Mol. Catal. A: Chem.*, 2006, **249**, 60–64; (d) J.-i. Ito and H. Nishiyama, *Synlett*, 2012, 509–523; (e) T. Wang, J.-L. Niu, S.-L. Liu, J.-J. Huang, J.-F. Gong and M.-P. Song, *Adv. Synth. Catal.*, 2013, **355**, 927–937.