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Chiral-at-Metal Ruthenium Complex as a Metalloligand for Asymmetric Catalysis

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The mononuclear $[Ru(bpy)_2(bpym)][PF_6]_2$ complex (bpy = 2,2′-bipyridine; bpym = 2,2′-bipyrimidine) has been prepared in its enantiopure Λ form. Because of the chelating property of the bipyrimidine moiety, it is possible to use this chiral-at-metal complex as a chiral inorganic ligand for a second metal cation acting as a catalytic center. Here we report the synthesis and the structural characterization of a novel dinuclear Λ-$[(bpy)_2Ru(bpym)RuCl(p\text{-cymene})]^{3+}$ compound (**1**). The asymmetric-inducing properties of the enantiopure chiral-at-metal metalloligand have been probed during asymmetric transfer hydrogenation to ketones catalyzed by **1**. This provides one of the very few illustrations of the potential of this original class of chiral inorganic ligands.

Introduction

In general, asymmetric metal-dependent catalysts are based on a combination of a metal ion at which the reaction takes place and a chiral organic ligand responsible for the asymmetric environment. However, at present, the inherent chirality of inorganic complexes (chirality Δ and Λ for octahedral complexes for example) as a source of such an asymmetric environment has been only very rarely exploited.[1] This approach requires that a method is available for the preparation of the chiral-at-metal complex in an enantiopure (or at least enantioenriched) form. This, in the absence of a chiral organic ligand, remains a challenging issue. Recently, using ruthenium based complexes, because of their well-known relative configurationnal stability, we demonstrated that chiral mononuclear complexes, in which the only stereogenic center was the metal ion itself, were able to catalyze asymmetric reactions.[2] An evolution of our research program was to design "chiral-at-metal" complexes so that they display free coordinating moieties for binding a second metal ion on which the reaction would take place. To our knowledge, such a strategy, based on chiral-at-metal metalloligand without any chiral organic ligand, was reported only once in the literature and was illustrated by rhodium/chiral rhenium dinuclear complexes as catalysts for enantioselective hydrosilylation of ketones and hydrogenation of dehydroamino acids.[3] Herein, we report our preliminary investigations in the development of an original dinuclear ruthenium complex bearing an enantiopure chiral metalloligand. Synthesis, characterization of this complex and evaluation of its catalytic properties regarding asymmetric transfer hydrogenation to ketones are reported.

Experimental Section

Materials. $Ru(bpy)_2Cl_2{\cdot}2H_2O$ was purchased from Strem Chemicals and 2,2′-bipyrimidine from Alfa Aesar. All the ketones used as substrates were commercially available. $Ru(dmp)_2Cl_2$[44] was prepared according to described procedure. $[Me_2NH_2][(\Delta,\delta)$-Binphat] was provided by J. Lacour (Université of Geneva, Geneva, Swizerland). Solvents used in synthetic procedures were analytical grade. All the experiments were carried under dark conditions to avoid any racemization process and under argon.

Instruments. NMR spectra were recorded on Bruker EMX 300 MHz. Electrospray mass spectrometry was performed on a Finnigan LC-Q instrument. Absorption spectra were recorded with a Hewlett-

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(1) Fontecave, M.; Hamelin, O.; Ménage, S. *Top. Organomet. Chem.* **2005**, *15*, 271−288.
(2) Chavarot, M.; Ménage, S.; Hamelin, O.; Charnay, F.; Pécaut, J.; Fontecave, M. *Inorg. Chem.* **2003**, *42*, 4810.
(3) Kromm, K.; Osburn, P. L.; Gladysz, J. A. *Organometallics* **2002**, *21*, 4275.
(4) Goldstein, A. S.; Beer, R. H.; Drago, R. S. *J. Am. Chem. Soc.* **1994**, *116*, 2424.

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Table 1. Selected Bond Lengths (Å) and Angles (deg) for Complexes [**1**][PF_6]$_3$, [**2**][PF_6]$_3$, [**4**][PF_6]$_2$, [**5**][Cl][a]

complex	bond (Å)		angle (deg)	
[**1**][PF_6]$_3$	Ru(1)−N(1)	2.067(3)	N(1)−Ru(1)−N(5)	100.25(11)
	Ru(1)−N(2)	2.053(3)	N(1)−Ru(1)−N(3)	172.63(11)
	Ru(1)−N(3)	2.061(3)	N(3)−Ru(1)−N(7)	94.82(11)
	Ru(1)−N(4)	2.062(3)	N(3)−Ru(1)−N(5)	86.30(11)
	Ru(1)−N(5)	2.083(3)	N(1)−Ru(1)−N(7)	89.74(11)
	Ru(1)−N(7)	2.081(3)	N(2)−Ru(1)−N(3)	95.04(12)
	Ru(2)−N(6)	2.109(3)	N(6)−Ru(2)−Cl	83.45(9)
	Ru(2)−N(8)	2.120(3)	N(8)−Ru(2)−Cl	81.99(9)
	Ru(2)−Cl	2.3978(12)	Ru(1)−Ru(2)−Cl	68.5
[**2**][PF_6]$_3$	Ru(1)−N(1)	2.095(3)	N(1)−Ru(1)−N(5)	93.85(13)
	Ru(1)−N(2)	2.105(3)	N(2)−Ru(1)−N(3)	100.59(14)
	Ru(1)−N(3)	2.103(3)	N(4)−Ru(1)−N(7)	80.36(13)
	Ru(1)−N(4)	2.122(3)	N(4)−Ru(1)−N(5)	95.76(13)
	Ru(1)−N(5)	2.093(3)	N(1)−Ru(1)−N(4)	101.66(13)
	Ru(1)−N(7)	2.092(3)	N(3)−Ru(1)−N(5)	171.10(13)
	Ru(2)−N(6)	2.118(3)	N(6)−Ru(2)−Cl	85.10(10)
	Ru(2)−N(8)	2.098(4)	N(8)−Ru(2)−Cl	82.85(11)
	Ru(2)−Cl	2.4067(15)	Ru(1)−Ru(2)−Cl	78.5
[**4**][PF_6]$_2$	Ru−N(1)	2.100(6)	N(2)−Ru−N(4)	101.7(2)
	Ru−N(2)	2.104(6)	N(1)−Ru−N(3)	101.5(2)
	Ru−N(3)	2.111(6)	N(2)−Ru−N(6)	81.6(2)
	Ru−N(4)	2.098(6)	N(3)−Ru−N(5)	81.4(2)
	Ru−N(5)	2.078(6)		
	Ru−N(6)	2.082(6)		
[**5**][Cl]	Ru−N(1)	2.090(4)	N(1)−Ru−Cl	81.79(13)
	Ru−N(2)	2.075(5)	N(2)−Ru−Cl	83.53(13)
	Ru−Cl	2.4016(15)		

[a] The estimated standard deviations in the least significant digits are given in parentheses.

Packard 8453 spectrometer. Circular dichroism spectra were recorded on a JASCO J-810 spectropolarimeter at 25 °C with a 1 cm path length cell. Data collection was performed at 298 K using a Bruker SMART diffractometer with a charged couple device (CCD) area detector, with graphite-monochromated Mo Kα radiation ($\lambda = 0.71073$ Å). The molecular structure was solved by direct methods and refined on F^2 by full matrix least-squares techniques using SHELXTL package with anisotropic thermal parameters. All non-hydrogen atoms were refined anisotropically, and hydrogen atoms were placed in ideal positions and refined as riding atoms with individual isotopic displacement parameters. Pertinent crystallographic data are summarized in Table 1.

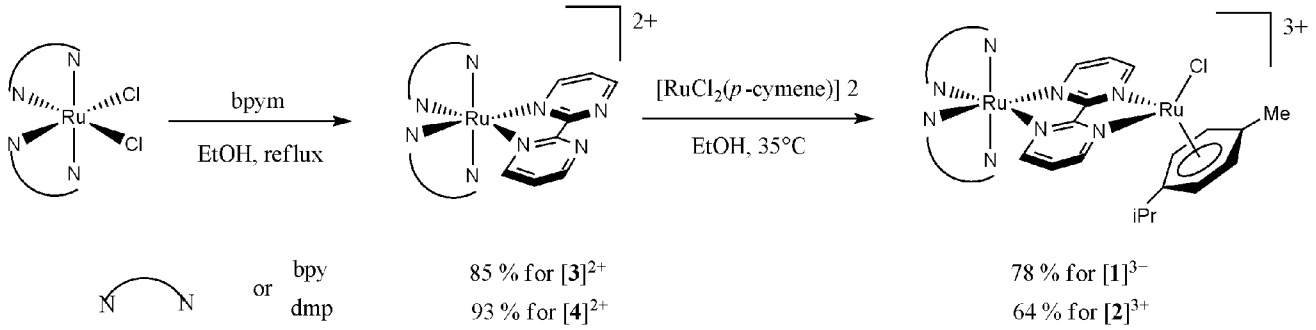
Synthesis of Compounds. *rac*-[(bpy)$_2$Ru(bpym)][PF_6]$_2$, (*rac*-[3][PF_6]$_2$). To a solution of Ru(bpy)$_2$Cl$_2$ (500 mg, 1.03 mmole) in absolute ethanol (90 mL), 2,2′-bipyrimidine (163.3 mg, 1.03 mmol) was added at once. The resulting solution was refluxed for 4 h. After concentration in vacuo, dissolution of the residue in water (addition of a small volume of ethanol is sometimes required for complete dissolution), the complex was precipitated by addition of NH_4PF_6 (1.67 g, 10,3 mmoles), filtrated, and washed three times with water. The resulting powder was dissolved in a minimum of acetone, and the complex precipitated once again by addition of the solution in a large volume of ether. After filtration, the complex was purified by silica gel chromatography (10%, 30% then 50% of (10% aqueous solution of saturated KNO_3 solution)−acetone). Metathesis of the anion was achieved after evaporation of the solvents, dissolution with a minimum of water and addition of NH_4PF_6 (1.67 g, 10.3 mmol). After filtration and drying in vacuo, the complex (755 mg, 85%) was obtained as a dark brown powder. ^{1}H NMR (300 MHz, acetone-d_6) δ 9.20 (dd, 2H, $J = 2.0$, 4.7 Hz), 8.88 (d, 4H, $J = 8.1$ Hz), 8.46 (dd, 2H, $J = 2.0$, 5.7 Hz), 8.26 (d, 2H, $J = 5.6$ Hz), 8.15−8.28 (m, 4H), 8.05 (d, 2H, $J = 5.1$ Hz), 7.72 (t, 2H, $J = 7.2$ Hz), 7.50−7.65 (ddd, 4H, $J = 6.6$, 6.6, 1.4 Hz); mass spectrum (ESI, acetone): *m*/*z* (relative intensity) 717 {[**3**][PF_6]}$^+$ (37), 286 {[**3**]}$^{2+}$ (100); UV−vis (CH_2Cl_2; λ_{max}, nm; ϵ, M^{-1} cm^{-1}) 240 (26 157), 286 (37 985), 425 (6478), 460 (4730); Anal. Calcd for $C_{28}H_{22}N_8F_{12}P_2Ru$,2 H_2O: C, 37.47; H, 2.92; Ru, 11.26. Found: C, 37.73; H, 2.82; Ru, 10.95.

Λ-[(bpy)$_2$Ru(bpym)][PF_6]$_2$, (Λ-[3][PF_6]$_2$). A solution of Λ-[(bpy)$_2$Ru(py)$_2$][dibenzoyl-L-tartrate] (623.0 mg, 0.67 mmol) and 2,2′-bipyrimidine (106.3 mg, 0.67 mmol) in ethylene glycol (240 mL) was heated at 120 °C for 5 h in dark then cooled to RT. Water (150 mL) then NH_4PF_6 (876.0 mg, 5.4 mmol) were added to the solution. Three extractions of the aqueous phase with dichloromethane, concentration in vacuo, and subsequent recrystallization by slow vapor diffusion of ether in an acetone solution of the complex gave the pure complex (472 mg, 81.5%) as a dark powder. Spectroscopic data are similar to the racemic mixture. CD for Λ-[(bpy)$_2$Ru(bpym)][PF_6]$_2$ (dichloromethane): λ_{max} ($\Delta\epsilon$) = 223 (−0.1), 235 (2.7), 305 (0.8), 376 (−2.3), 500 (1.02 M^{-1} cm^{-1}).

***rac*-[(dmp)$_2$Ru(bpym)][PF_6]$_2$, (*rac*-[4][PF_6]$_2$).** The dmp complex was prepared in an analogous manner to *rac*-[(bpy)$_2$Ru(bpym)]-[PF_6]$_2$ except that Ru(dmp)$_2$Cl$_2$ was used in place of Ru(bpy)$_2$Cl$_2$. The complex was obtained in 93% yield. Single crystals were obtained by slow diffusion of ether in a solution of the complex in acetone. ^{1}H NMR (300 MHz, acetone-d_6) δ 9.01 (dd, 2H, $J = 1.9$, 4.7 Hz), 8.88 (d, 2H, $J = 8.4$ Hz), 8.59 (d, 2H, $J = 8.4$ Hz), 8.42 (d, 2H, $J = 8.7$ Hz), 8.31 (d, 2H, $J = 8.7$ Hz), 7.98 (d, 2H, $J = 8.7$ Hz), 7.81 (dd, 2H, $J = 1.9$, 5.9 Hz), 7.68 (d, 2H, $J = 8.4$ Hz), 7.38 (dd, 2H, $J = 4.7$, 5.9 Hz), 2.18 (s, 6H), 2.10 (s, 6H); mass spectrum (ESI, acetone): *m*/*z* (relative intensity) 821 {[**4**][PF_6]}$^+$ (31), 338 {[**4**]}$^{2+}$ (100); MS (ESI$^-$, acetone): *m*/*z* (%) 1111 {[**4**][PF_6]$_3$}$^-$ (100); UV−vis (CH_2Cl_2; λ_{max}, nm; ϵ, M^{-1} cm^{-1})) 232 (62 212), 268 (72 439), 305 (19 583), 385 (9573), 432 (8685), 482 (4588); Anal. Calcd for $C_{36}H_{30}N_8F_{12}P_2Ru$, 3$H_2O$: C, 42.40; H, 3.56; N, 10.99; Ru, 9.91. Found: C, 42.88; H, 3.28; N, 11.10; Ru, 9.33; crystallographic data: monoclinic, $P2(1)/c$, $a = 17.768(3)$ Å, $b = 13.746(2)$ Å, $c = 18.781(3)$ Å, $V = 4586.2(14)$ Å^3, $Z = 4$, $R = 0.0876$, $R_w = 0.2270$. (CCDC 615941).

***rac*-[Ru(bpy)$_2$(bpym)RuCl(*p*-cymene)][NO_3]$_3$, (*rac*-[1][NO_3]$_3$).** A solution of *rac*-[**3**][PF_6]$_2$ (30 mg, 34.8 μmol) in absolute ethanol (5 mL) and [$RuCl_2$(*p*-cymene)]$_2$ (10.6 mg, 17.4 μmol) was heated to 35 °C for 3 h under argon atmosphere. The resulting solution was concentrated and purified by silica gel chromatography (30% of (10% aqueous solution of saturated KNO_3 solution)−acetone. After evaporation of the solvent, the excess of KNO_3 was precipitated by addition of ethanol and then filtered off. This procedure was repeated twice and afforded the pure complex (28 mg, 78%) as a dark powder. ^{1}H NMR (300 MHz, methanol-d_4) δ 9.84 (dd, 1H, $J = 5.6$, 1.2 Hz), 9.78 (dd, 1H, $J = 5.7$, 1.3 Hz), 8.72 (d, 1H, $J = 8.0$ Hz), 8.71 (d, 1H, $J = 8.0$ Hz), 8.62 (t, 2H, $J = 8.3$ Hz), 8.40−8.60 (m, 2H), 8.35 (dd, 1H, $J = 5.6$, 1.2 Hz), 8.05−8.30 (m, 4H), 7.88 (t, 1H, $J = 5.7$ Hz), 7.84 (t, 1H, $J = 5.7$ Hz), 7.72 (t, 2H, $J = 5.2$ Hz), 7.60−7.70 (m, 2H), 7.30−7.60 (m, 3H), 6.30 (m, 2H), 6.17 (m, 2H), 3.29 (h, 1H, $J = 6.7$ Hz), 2.26 (s, 3H), 1.32 (d, 3H, $J = 6.7$ Hz), 1.30 (d, 3H, $J = 6.7$ Hz); MS (ESI$^+$, H_2O): *m*/*z* (%) 967 {[**1**][NO_3]$_2$}$^+$ (3), 452 {[**1**][NO_3]}$^{2+}$ (100), 286 {[**3**]}$^{2+}$; mass spectrum (ESI, methanol): *m*/*z* (relative intensity) 936 {[**1**][MeO,NO_3]$_2$}$^+$ (3), 436 {[**1**][MeO]}$^{2+}$ (23), 286 {[**3**]}$^{2+}$ (100); UV−vis (H_2O; λ_{max}, nm; ϵ, M^{-1} cm^{-1})) 243 (26 264), 277 (40 121), 310 (10 897), 415 (23 414), 575 (3296); HRMS (ES) for $C_{38}H_{36}N_8F_{12}P_2ClRu_2$; calcd 1133.0122; Found 1133.0101; Anal. Calcd for $C_{38}H_{36}N_{11}O_9Ru_2Cl$·2$KNO_3$·2EtOH: C, 38.14; H, 3.66; N, 13.77; Cl, 2.68. Found: C, 37.95; H, 3.42; N, 13.71; Cl, 3.17; crystallographic data: triclinic, $P\bar{1}$, $a = 13.271(2)$ Å, $b = 13.698(2)$ Å, $c = 16.882(3)$ Å, $V = 2540.1(7)$ Å^3, $Z = 2$, $R = 0.0595$, $R_w = 0.1133$. (CCDC 615939).

Scheme 1. Preparation of the Catalysts $[\mathbf{1}]^{3+}$ and $[\mathbf{2}]^{3+}$



Λ-[Ru(bpy)$_2$(bpym)RuCl(*p*-cymene)][NO$_3$]$_3$, (Λ-[1][NO$_3$]$_3$). The compound Λ-[**1**][NO$_3$]$_3$ was prepared following the procedure used for *rac*-[**1**][NO$_3$]$_3$ and was obtained in similar yield. CD for Λ-[**1**][NO$_3$]$_3$ (H$_2$O): λ_{max} ($\Delta\epsilon$) = 220 (11.3), 242 (3.2), 292 (3.1), 276 (3.0), 391 (−2.1)(M^{-1} cm^{-1}).

***rac*-[Ru(dmp)$_2$(bpym)RuCl(*p*-cymene)][NO$_3$]$_3$, (*rac*-[2][NO$_3$]$_3$).** The compound *rac*-[**2**][NO$_3$]$_3$ was prepared using the same procedure as for *rac*-[**1**][PF$_6$]$_2$ and was obtained in 64% yield. ^{1}H NMR (300 MHz, methanol-d_4) δ 9.65 (dd, 1H, J = 5.1, 1.5 Hz), 9.56 (dd, 1H, J = 5.4, 0.9 Hz), 8.79 (d, 2H, J = 8.4 Hz), 8.51 (d, 1H, J = 8.1 Hz), 8.36 (d, 1H, J = 8.4 Hz), 8.20−8.40 (m, 3H), 8.13 (d, 1H, J = 8.7 Hz), 7.89 (d, 1H, J = 8.7 Hz), 7.86 (d, 1H, J = 8.4 Hz), 7.79 (dd, 2H, J = 5.7, 1.2 Hz), 7.60 (d, 1H, J = 8.1 Hz), 7.55−7.35 (m, 4H), 6.16 (t, 2H, J = 6.3 Hz), 5.99 (m, 2H), 2.88 (h, 1H, J = 6.9 Hz), 2.34 (s, 3H), 2.10 (s, 3H), 2.00 (s, 3H), 1.99 (s, 3H), 1.97 (s, 3H), 1.26 (d, 3H, J = 7.2 Hz), 1.24 (d, 3H, J = 7.2 Hz); mass spectrum (ESI, water): *m*/*z* (relative intensity) 1071 {[**2**][NO$_3$]$_2$}$^+$ (2), 504 {[**2**][NO$_3$]}$^{2+}$ (55), 338 {[**4**]}$^{2+}$ (100); MS (ESI$^+$, MeOH): *m*/*z* (%) 1040 {[**2**][MeO,NO$_3$]$_2$}$^+$ (6),436 {[**2**]-[MeO]}$^{2+}$ (27), 286 {[**3**]}$^{2+}$ (100); UV−vis (H$_2$O; λ_{max}, nm; ϵ, M^{-1} cm^{-1}) 265 (38 900), 295 (18 284), 370 (7294), 430 (9256), 600 (3612); Anal. Calcd for for C$_{46}$H$_{44}$N$_8$Ru$_2$ClP$_3$F$_{18}$, 4H$_2$O: C, 38.01; H, 3.61; N, 7.71; Cl, 2.44. Found: C, 38.28; H, 3.16; N, 7.77; Cl, 2.44; crystallographic data: monoclinic, $P2(1)/c$, a = 15.566(5) Å, b = 17.247(5) Å, c =25.599(8) Å, V = 6711(4) Å^3, Z = 4, R = 0.0963, R_w = 0.1745. (CCDC 615940).

[(bpym)RuCl(*p*-cymene)][Cl], ([5][Cl]). A solution of [RuCl$_2$-(*p*-cymene)]$_2$ (200 mg, 653.0 μmol) and 2,2′-bipyrimidine (105 mg, 664.0 μmol) in absolute ethanol (50 mL) was refluxed for 4 h. The resulting yellow solution was concentrated in vacuo. The crude product was solubilized in a minimum of ethanol, and the complex was precipitated by addition of the solution in a large volume of ether. After drying in vacuo, the complex was obtained as a yellow solid (285 mg, 94%). ^{1}H NMR (300 MHz, acetone-d_6) δ 9.89 (dd, 2H, J = 5.7, 2.1 Hz), 9.31 (dd, 2H, J = 4.8, 2.1 Hz), 8.00 (d, 2H, J = 5.7, 4.8 Hz), 6.31 (d, 2H, J = 6.3 Hz), 6.12 (d, 2H, J = 6.3 Hz), 2.91 (h, 1H, J = 6.9 Hz), 2.27 (s, 3H), 1.19 (d, 6H, J = 6.9 Hz); mass spectrum (ESI, methanol): *m*/*z* (relative intensity) 429 {[**5**]}$^+$ (100); UV−vis (MeOH; λ_{max}, nm; ϵ, M^{-1} cm^{-1}) 211 (20 493), 240 (17 152), 425 (4826), 635 (2354); Anal. Calcd for for C$_{18}$H$_{20}$N$_4$RuCl$_2$, 3H$_2$O: C, 41.70; H, 5.06; N, 10.81; Cl, 13.68. Found: C, 41.26; H, 4.09; N, 10.84; Cl, 13.58; crystallographic data: monoclinic, $P2(1)/n$, a = 14.272(6) Å, b = 16.680(7) Å, c =16.871(7) Å, V = 3976(2) Å^3, Z = 8, R = 0.0924, R_w = 0.1743. (CCDC 615942).

Standard Conditions for Transfer Hydrogenation of Ketones. The reaction was carried out under argon atmosphere, and care was taken to avoid exposure to light. To a solution of HCO$_2$Na (897.5 mg, 13.20 mmol) in water (6 mL) whose pH was adjusted to 4 by addition of pure HCO$_2$H (295 μL); the catalyst (2.17 μmol) was then added. The resulting solution was then heated to 80 °C before addition of the substrate (434.00 μmol).The reaction mixture was then stirred at 80 °C for 24 h, and the product was extracted three times with CH$_2$Cl$_2$. After concentration in vacuo, the resulting mixture was analyzed and quantified (TON and ee) by ^{1}H NMR and chiral GC.

Enantiomeric Excesses Determination. Enantiomeric excesses of the alcohols were determined by GC using two different chiral columns (Lipodex E from Macherey-Nagel and B-PM from Chiraldex).

Results and Discussion

Preparation of the Complexes. The syntheses of two new original dinuclear ruthenium complexes *rac*-[(diimine)$_2$Ru-(bpym)RuCl(p-cymene)][NO$_3$]$_3$ (diimine = bipyridine (bpy) for compound [**1**][NO$_3$]$_3$ or 2,9-dimethyl-1,10-phenanthroline (dmp) for compound [**2**][NO$_3$]$_3$; bpym = 2,2′-bipyrimidine) were easily and efficiently achieved in two steps from commercially available [Ru(bpy)$_2$Cl$_2$] for [**1**]$^{3+}$ and [Ru-(dmp)$_2$Cl$_2$][5] for [**2**]$^{3+}$ (Scheme 1). First, *rac*-[**3**][PF$_6$]$_2$ and *rac*-[**4**][PF$_6$]$_2$ were obtained by substitution of the two chloro ligands by the bpym bridging ligand. Subsequent reaction of *rac*-[**3**][PF$_6$]$_2$ and *rac*-[**4**][PF$_6$]$_2$ with [RuCl$_2$(p-cymene)]$_2$ followed by anion metathesis during the chromatographic purification afforded the complexes *rac*-[**1**][NO$_3$]$_3$ and *rac*-[**2**][NO$_3$]$_3$ in 66% and 60% overall yield, respectively. The complex [**5**][Cl] was easily prepared in high yield (94%) by refluxing an ethanolic solution of [RuCl$_2$(p-cymene)]$_2$ in the presence of 1 equiv of bpym for 4 h.

Single crystals suitable for X-ray analysis were obtained by slow diffusion of diethylether into solutions of the complexes in acetone for [**1**] [PF$_6$]$_3$, [**2**][PF$_6$]$_3$, and [**4**][PF$_6$]$_2$ and slow diffusion of an ether−acetone mixture into a solution of the complex in an ethanol−acetonitrile mixture for [**5**][Cl]. The X-ray crystal three-dimensional structures of the complexes are shown in Figure 1. For [**5**][Cl], angles and bond lengths are in the range to those reported for the complex [(η^6-C$_6$Me$_6$)Ru(bpy)(H$_2$O)]$^{2+}$.[5] Selected bond lengths and angles are listed in Table 1. Complex [**4**][PF$_6$]$_2$ shows an highly distorted octahedral geometry, probably due to the steric repulsion generated by one of the two methyls substituents of each of the dmp ligands in combination with the fact that the bite angle of the phenanthroline chelates is less than 90°. Indeed some cis N−Ru−N angles are increased

(5) Hogo, S.; Abura, T.; Watanabe, T. *Organometallics* **2002**, *21*, 2964.

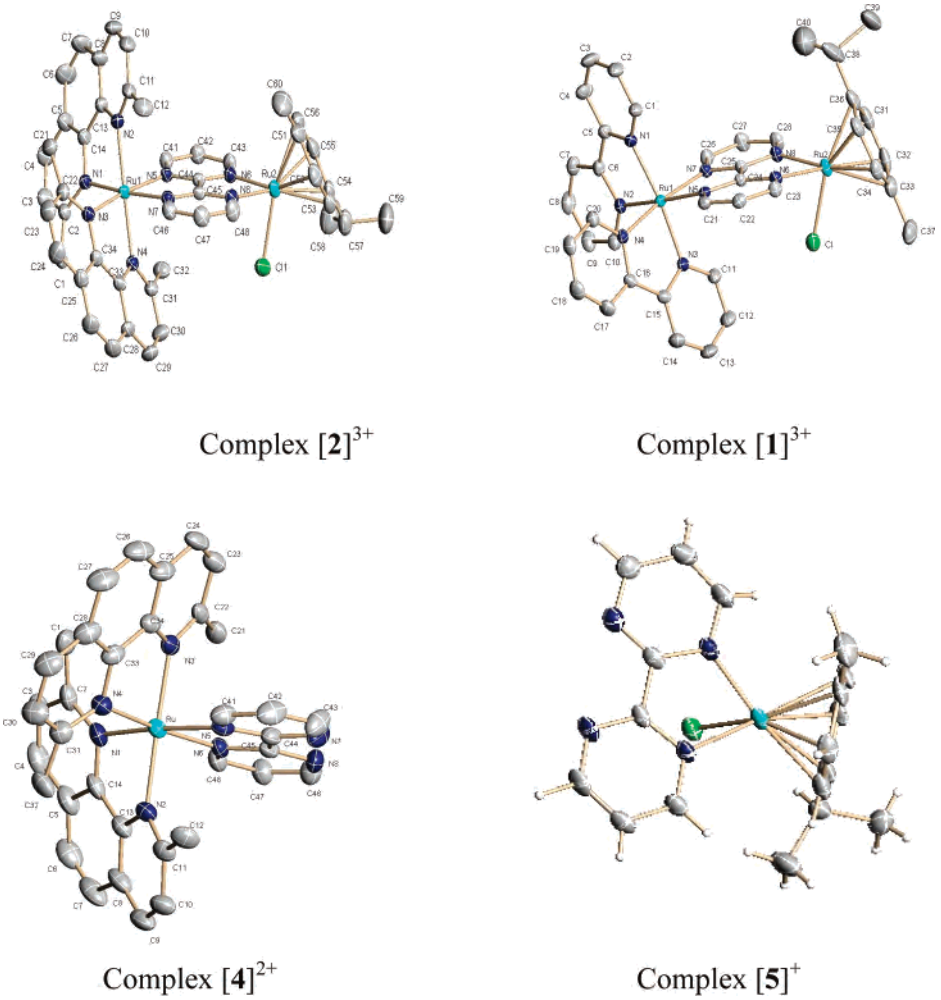


Figure 1. ORTEP views of the structures of $[\mathbf{1}]^{3+}$, $[\mathbf{2}]^{3+}$, $[\mathbf{4}]^{2+}$, and $[\mathbf{5}]^{+}$. Hydrogen atoms have been omitted for clarity.

by as much as 11° with regard to those of a pure octahedron, whereas some others are decreased by about 9°. This is also true for complex $[\mathbf{2}]^{3+}$ and was also observed in the case of other members of the $[(dmp)_2RuXX']^{2+}$ family.[6] It is noticeable that such a deformation is not as high when bpy is use in place of dmp ligand. For example, the N(1)−Ru(1)−N(3) angle is 101.7° in $[\mathbf{2}]^{3+}$ and $[\mathbf{4}]^{2+}$, whereas the corresponding N(2)−Ru(1)−N(3) angle is 95.04° in $[\mathbf{1}]^{3+}$. Also, it is worth noting that a steric repulsion between the isopropyl residue and one of the two bipyridines in complex $[\mathbf{1}]^{3+}$ generates an important curvature of the bridging bpym ligand. Such a phenomenon is not observed in complex $[\mathbf{2}]^{3+}$. This leads to an important effect on the position of the chloro ligand with regard to the Ru(1)−Ru(2) axis. Indeed, the Ru(1)−Ru(2)−Cl angle is 68.5° in $[\mathbf{1}]^{3+}$ and 78.7° in $[\mathbf{2}]^{3+}$.

Preparation of the Enantiopure Complexes. It was reported that substitution by mono- or bidentate ligands of one or the two pyridine ligands of the chiral compound (Δ- or Λ-) $[Ru(bpy)_2py_2]^{2+}$ could be done without any racemization.[7] Consequently, Λ-$[Ru(bpy)_2py_2]$[(−)-*O*,*O*′-dibenzoyl-L-tartrate] was prepared according to literature procedures.[8] Displacement of both pyridine ligands by bipyrimidine was then achieved in hot ethylene glycol solution.[9] After anion metathesis, extraction with dichloromethane and recrystallization by slow diffusion of ether in a solution of the crude complex in acetone, $[\mathbf{3}][PF_6]_2$ was obtained in 81% yield. The latter was then converted to complex $[\mathbf{1}]^{3+}$ as described for the racemic complex with similar yield. The absolute configuration Λ for $[\mathbf{1}][NO_3]_3$ and $[\mathbf{3}][PF_6]_2$ was assigned by comparison with the CD spectrum obtained from the initial Λ-$[Ru(bpy)_2py_2]$[(−)-*O*,*O*′-dibenzoyl-L-tartrate] complex (Figure 2).[10] Indeed, the three complexes show a similar spectral pattern with with Cotton effects of the same sign in absorption wavelength regions of electronic transitions common to all off them. In contrast, we were unable to obtain $[\mathbf{4}]^{2+}$ and thus $[\mathbf{2}]^{3+}$ in their enantiomerically pure or enriched forms by resolution.

The enantiomeric purity of Λ-$[\mathbf{1}]^{3+}$ was determined by ^{1}H NMR using Binphat[11] as a chiral shift reagent. The NMR spectra of *rac*-$[\mathbf{1}][PF_6]_3$ and Λ-$[\mathbf{1}][PF_6]_3$ obtained from their

(6) Hamelin, O.; Pécaut, J.; Fontecave, M. *Chem. Eur. J.* **2004**, *10*, 2548.
(7) (a) Brissard, M.; Convert, O.; Gruselle, M.; Guyard-Duhayon, C.; Thouvenot, R. *Inorg. Chem.* **2003**, *42*, 1378. (b) Hui, C.; Jin-Gang, L.; Cai-Wu, J.; Liang-Nian, J.; Xiao-Yuan, L.; Chuan-Li, F. *Inorg. Chem. Commun.* **2001**, 45. (c) Hua, X.; von Zelewsky, A. *Inorg. Chem.* **1995**, *34*, 5791.
(8) (a) Hua, H.; von Zelewsky, A. *Inorg. Chem.* **1995**, *34*, 5791. (b) Hua, X.; von Zelewsky, A. *Inorg. Chem.* **1995**, *34*, 992.
(9) Tzalis, D.; Tor, Y. *J. Am. Chem. Soc.* **1997**, *119*, 852.
(10) (a) Bosnich, B. *Acc. Chem. Res.* **1969**, *2*, 266. (b) Richardson, F. S. *Chem. Rev.* **1979**, *79*, 17. (c) Ziegler, M.; von Zelewsky, A. *Coord. Chem. Rev.* **1998**, *177*, 257. (d) See also ref 8c.

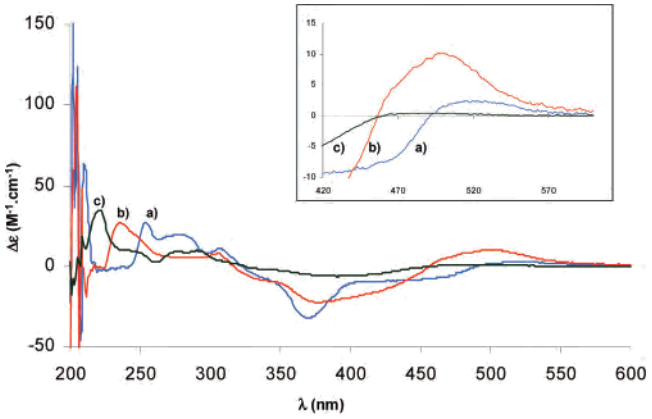


Figure 2. Circular dichroism spectra of Λ-[Ru(bpy)$_2$Py$_2$][(−)-*O*,*O*′-dibenzoyl-L-tartrate] in water (30 μM) (a), of [**3**][PF$_6$]$_2$ in dichloromethane (30 μM) (b), and of [**1**][NO$_3$]$_3$ in water (65 μM) (c).

NO_3 salts by simple anion metathesis were recorded after dissolution in acetone-d_6 in the presence of [Me_2NH_2][(Δ,*S*)-Binphat] and compared to those of the same solutions in the absence of the chiral salt (Figure 3). Addition of an excess (2.8 equiv) of [Me_2NH_2][(Δ,*S*)-Binphat] to the solution of the racemic mixture results in an impressive shift of the resonances corresponding to the protons of the *p*-cymene moiety, suggesting a $\pi-\pi$ interaction between the cymene ring and one of the aromatic rings of the Binphat. For example, the singulet at 2.32 ppm corresponding to the methyl substituent of the *p*-cymene was shifted and split into two singulets at 1.49 and 1.71 ppm (localized by a star in Figure 3). Such a π-stacking involving the Trisphat anion was also observed by Amouri in the *trans*-[(*S*p,*S*p)-bis-(Cp*Ru)-carbazolyl][Δ-Trisphat] complex bearing a planar chirality.[12] On the other hand, when Binphat was added to a

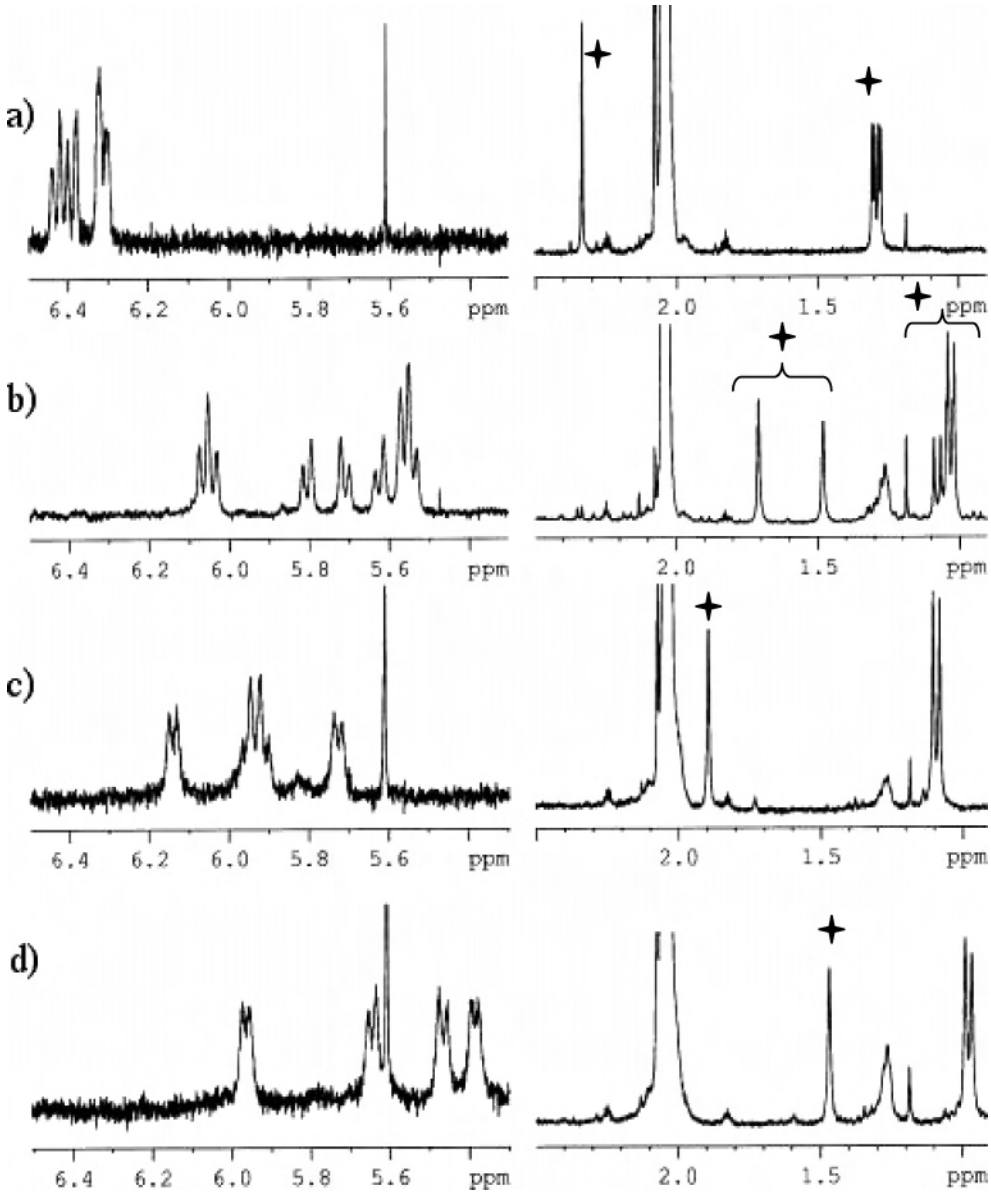


Figure 3. ^{1}H NMR spectra (300 MHz, acetone-d_6) of the aromatic and aliphatic protons of the *p*-cymene moiety for the racemic [**1**][PF$_6$]$_3$ in the absence (a) and in the presence (b) of 2.8 equiv of [Me_2NH_2][(Δ,*S*)-Binphat] and for the Λ-[**1**][PF$_6$]$_3$ in the presence of 1.7 (c) and 4.8 (d) equiv of [Me_2NH_2]-[(Δ,*S*)-Binphat].

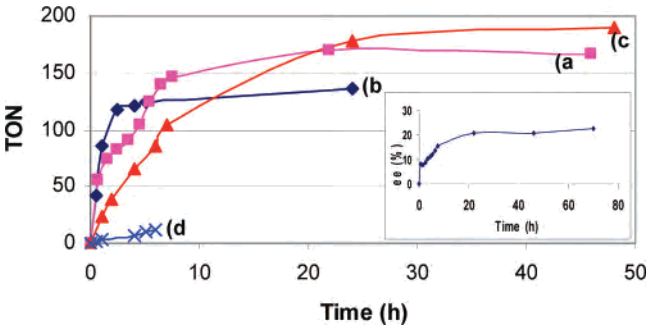


Figure 4. Catalytic hydrogen transfer to acetophenone using [**1**][NO_3]$_3$, (a); [**2**][NO_3]$_3$, (b); [**5**][Cl], (c) and [$RuCl_2$(*p*-cymene)]$_2$ (d). Inset; evolution of the enantiomeric excess during the course of the hydrogenation of acetophenone with Λ-[**1**][NO_3]$_3$ as a catalyst.

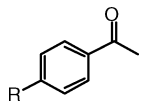
solution of Λ-[**1**]$^{3+}$, only one singlet and one doublet were observed for the two types of methyl groups, thus demonstrating the enantiopurity of [**1**]$^{3+}$ (Figure 4).

Asymmetric Catalytic Transfer Hydrogenation. Hydrogenation of acetophenone to the corresponding alcohol using sodium formate as hydrogen donor in water was then investigated as the probe reaction with racemic complexes.[6] Assays were carried out first with the water soluble *rac*-[**1**]-[NO_3]$_3$ and *rac*-[**2**][NO_3]$_3$ complexes and their reactivity compared to that of [**5**][Cl] and of the commercially available [$RuCl_2$(*p*-cymene)]$_2$ (Figure 2). All the experiments were achieved under argon atmosphere and care was taken to avoid exposure to light. After dissolution of the complex (0.36 mM) in an aqueous solution of sodium formate (2.16 M), whose pH was adjusted to 4 by controlled addition of pure formic acid and subsequent heating to 80 °C, the substrate (72 mM) was added. The reaction product was identified and quantified by GC-MS and ^{1}H NMR. While [$RuCl_2$(*p*-cymene)]$_2$ was inactive, moderate to good catalytic activities were obtained with [**2**][NO_3]$_3$ (68% yield, 120 TON after 4 h), [**1**][NO_3]$_3$ (85%, 180 TON after 20 h), and [**5**][Cl] (95%, 190 TON after 35 h) (Figure 4). Examination of the initial rates shows that the dinuclear compounds [**1**][NO_3]$_3$ and [**2**][NO_3]$_3$ were significantly more active than the mononuclear [**5**][Cl] species. Thus, coupling of the active Ru(*p*-cymene) moiety to a Ru(diimine) moiety is beneficial. Moreover, we observed that when nitric acid was used in order to adjust the pH, as was described by Watanabe and co-workers, the reaction did not work.

The enantiopure catalyst Λ-[**1**][NO_3]$_3$ was then assayed during hydrogenation of a variety of ketones using the previously described procedure (catalyst/substrate/HCO_2Na = 0.36:72:2160 mM, pH 4). All the reactions were stopped after 24 h, and the resulting products were extracted with dichloromethane. Conversion and TON were both calculated from the resulting ^{1}H NMR spectrum and from the amount of remaining substrate. The enantiomeric excesses (ee's) of the products were determined by chiral GC with the exception of 2-(2-hydroxyethyl)-pyridine for which the ee was determined by ^{1}H NMR using a large excess of (*S*)-1,1′-binaphtol as a chiral shift reagent. As can be observed in Table 2, conversions of aryl methylketones are moderate to excellent ranging from 15% to 100%. As was expected, the more electron-attracting the aryl substituent, the more efficient the reaction. For instance, the hydrogenation of 4-methoxyphenylacetone was achieved with 44% conversion, whereas 100% conversion was obtained whith trifluoromethyl as the substituent (entries 1a and 1e, respectively). Interestingly, in the case of 4-nitrophenylacetone, a selective and quantitative hydrogenation of the nitro group was observed (entry 1d). Due to the very low reactivity of the resulting 4-aminophenylacetone, no further hydrogenation could be observed. Reduction of ethylacetoacetate afforded the ethyl-3-hydroxybutyrate as the unique product resulting from the chemioselective hydrogenation of the keto group (entry 7). Finally, hydrogenation of two α−β unsaturated ketones yielded to the resulting saturated alcohols (entries 9 and 10).

Finally, we observed that only alkyl aryl ketones afforded significant, albeit low, ee's ranging from 18% to 26% with the exception of *p*-methoxyphenylacetone which, in addition, showed low reactivity (entry 1a). However, while these ee values are relatively smaller than the ones reported in the

Table 2. Enantioselective Transfer Hydrogenation of Ketones with Λ-[**1**][NO_3]$_3$ as a Catalyst[a]

entries	substrate		product(s)	TON[b]	conversion[c]	ee (%)
1a		R= OCH_3	*p*-methoxyphenyl ethanol	88	44	3
1b		R= CH_3	*p*-methylphenyl ethanol	146	73	18
1c		R= H	1-phenylethanol	156	78	26 (*S*)
1d		R= NO_2	*p*-aminophenylacetone	400	100	–
1e		R= CF_3	*p*-trifluoromethyl phenylethanol	200	100	21
2	2-acetylpyridine		2-(2-hydroxyethyl) pyridine	168	84	22[b]
3	2′-acetonaphtone		methyl-2-naphthtalene methanol	170	85	26
4	1′-acetonaphtone		methyl-1-naphthtalene methanol	156	78	21
5	4-methyl tetralone		4-methyl-1,2,3,4-tetrahydro-naphtalen-1-ol (diastereomeric ratio; 1:1.1)	30	15	not determined
6	indan-2-one		indan-2-ol	165	82.5	–
7	ethylacetoacetate		ethyl-3-hydroxybutyrate	191	95.5	0[d]
8	4-phenylbutan-2-one		4-phenylbutan-2-ol	148	74	0
9	cyclohex-2-en-1-one		cyclohexanol	224	100	–
			cyclohexanone (1.3:1)	88		
10	(*E*)-4-phenyl-but-3-en-2-one		4-phenylbutan-2-ol	91	100	0
			4-phenylbutan-2-one (1:3.4 ratio)	155		

[a] The reaction was carried out at 80 °C using a ketone (0.43 mmol) in H_2O (6 mL) with Λ-[**1**][NO_3]$_3$/ketone/HCOONa = 1:200:6000. [b] Work up after 24 h of reaction; measured by ^{1}H NMR. [c] ^{1}H NMR determination using a large excess of (*S*)-(−)-1,1′-binaphtol as a chiral NMR shift reagent. [d] ^{1}H NMR determination using Tris[3-(trifluoromethyl-hydroxymethylen)-D-camphorato]-europium as a chiral NMR shift reagent.

literature for the most efficient hydrogen-transfer asymmetric catalysts,[13] an interesting amplification of the chirality during the course of the hydrogenation of acetophenone was observed (Figure 2, Inset). Indeed, while the enantiomeric excess was only of about 8% after 72 TON (1.5 h), it reached 20% after 169 TON (22 h). The same was observed with 2′-acetonaphtone (from 17% ee (6 h) to 26% (24 h); data not shown) suggesting an asymmetric autoinduction. Such an amplification of the chirality has been rarely observed, however, in most cases with much larger final ee's than those reported here.[14] Further experiments are required to define the molecular basis for the observed phenomenon. In particular, evidence for the formation of an interaction between the product and Λ-[**1**]$^{3+}$ should be searched for.

Conclusion

The novel class of chiral catalysts, based on a chiral-at-metal metalloligand, for asymmetric catalysis opens a new research direction. Obviously, further developments are required to rival with the most efficient asymmetric transfer hydrogenation catalysts developed to date bearing chiral organic ligands. However, this first generation of catalysts showed good catalytic activity with several hundred TON. Other reactions will be investigated in the future using this strategy.

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Supporting Information Available: Crystallographic data for [**1**][PF_6]$_3$, [**2**][PF_6]$_3$, [**4**][PF_6]$_2$, and [**5**][Cl] (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) (a) Lacour, J.; Londez, A.; Goujon-Ginglinger, C.; Buss, V.; Bernardinelli, G. *Org. Lett.* **2000**, *2*, 4185. (b) Lacour, J.; Hebbe-Viton, V. *Chem. Soc. Rev.* **2003**, *32*, 373, and references cited therein.

(12) (a) Amouri, H.; Caspar, R.; Gruselle, M.; Guyard-Duhayon, C.; Boubekeur, K.; Lev, D. A.; Collins, L. S. B.; Grotjahn, D. B. *Organometallics* **2004**, *23*, 4338. See also (b) Govindaswamy, P.; Linder, Lacour, J.; Süss-Fink, G.; Therrien, B. *Chem. Commun*. **2006**, 4691.

(13) (a) Doucet, H.; Ohkuma, T.; Murata, K.; Yokozawa, T.; Katayama, E.; England, A. F.; Ikaria, T.; Noyori, R. *Angew. Chem., Int. Ed.* **1998**, *37*, 1703. (b) Moris, D. J.; Hayes, A. M.; Wills, M. *J. Org. Chem.* **2006**, *71*, 7035. (c) Reetz, M.; Li, X. *J. Am. Chem. Soc*. **2006**, *128*, 1044. (d) Hayes, A. M.; Morris, D. J.; Clarkson, G. J.; Wills, M. *J. Am. Chem. Soc*. **2005**, *127*, 7318. (e) Ohkuma, T.; Utsumi, N.; Tsutsumi, K.; Murata, K.; Sandoval, C.; Noyori, R. *J. Am. Chem. Soc.* **2006**, *128*, 8724. (f) Västilä, P.; Zaitsev, A. B.; Wettegren, J.; Privalov, T.; Adolfsson, H. *Chem. Eur. J*. **2006**, *12*, 3218.

(14) (a) Trost, B. M.; Fettes, A.; Shireman, B. T. *J. Am. Chem. Soc.* **2004**, *126*, 2660. (b) Szlosek, M.; Figadere, B. *Angew. Chem. Int. Ed.* **2000**, *39*, 1799. (c) Kogut, E. F.; Thoen, J. C.; Lipton, M. A. *J. Org. Chem.* **1998**, *63*, 4604. (d) Heller, D. P.; Goldberg, D. R.; Wulff, W. D. *J. Am. Chem. Soc*. **1997**, *119*, 10551. (e) Danda, H.; Nishikawa, H.; Otaka, K. *J. Org. Chem.* **1991**, *56*, 6740. (f) Alberts, A. H.; Winberg, H. *J. Am. Chem. Soc.* **1989**, *111*, 7265.