Enantioselective Epoxidation of Unfunctionalized Alkenes by a Chiral Monooxoruthenium(IV) Complex $[RuL(bpy)O]^{2+}$ {L = 2,6-bis[(4*S*,7*R*)-7,8,8-trimethyl-4,5,6,7-tetrahydro-4,7-methanoindazol-2-yl]pyridine; bpy = 2,2′-bipyridine}

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A new chiral monooxoruthenium(IV) complex containing 2,6-bis[(4*S*,7*R*)-7,8,8-trimethyl-4,5,6,7-tetrahydro-4,7-methanoindazol-2-yl]pyridine and 2,2′-bipyridine ligands is prepared and the X-ray crystal structure of its $Ru^{II}–OH_2$ precusor determined; this $Ru^{IV}=O$ complex catalyses epoxidation of unfunctionalized alkenes with promising enantioselectivity.

An important challenge in asymmetric catalysis is to elucidate the various factors affecting the enantiomeric excess of chiral organic products. In this context, it is essential both to characterize and to study the reactive intermediate(s) in metal catalysed asymmetric organic reactions. However, despite the success of the various chiral iron and manganese catalysts in asymmetric alkene epoxidation,[1] the proposed chiral metal–oxo reactive intermediate remains elusive and has been neither isolated nor properly characterised. Thus it is interesting to learn whether a well defined chiral metal–oxo complex would undergo asymmetric oxygen atom transfer to alkene or not. Herein is described a monooxoruthenium(IV) complex containing a C_2 symmetric chiral tridentate imine and a 2,2′-bipyridine ligand, $[Ru^{IV}L(bpy)O]^{2+}$ {L = 2,6-bis[(4*S*,7*R*)-7,8,8-trimethyl-4,5,6,7-tetrahydro-4,7-methanoindazol-2-yl]pyridine}. It is one of only a few chiral ruthenium–oxo complexes[2,3] and is the first chiral metal–oxo complex reported to undergo enantioselective epoxidation of unfunctionalized alkenes with moderate enantioselectivities.

The ligand L was prepared from (1*R*)-(+)-camphor by the procedure developed by Steel and co-workers.[4] Its spectroscopic data are in agreement with the literature values. $[Ru^{III}LCl_3]$ **1**‡ was prepared by refluxing $RuCl_3·3H_2O$ (1 equiv.) with L (1.1 equiv.) in ethanol (100 cm^3). Complex **1** is a green solid. Its reaction with bipy (1 equiv.) and LiCl in the presence of zinc metal powder in ethanol gave $[Ru^{II}L(bpy)Cl]PF_6$ **2a** in a nearly quantitative yield. Reacting **2** with Ag^I in acetone–water (4 : 1, *v*/*v*) gave $[Ru^{II}L(bpy)(OH_2)][PF_6]_2$ **3a** as an orange salt by slow evaporation of acetone. The perchlorate salt **3b** was similarly prepared from $[Ru^{II}L(bpy)Cl]ClO_4$ **2b**. Circular dichroism measurement revealed that **3** displays a strong couplet at 370 nm. Its ^1H NMR spectrum showed that the two camphor-pyrazole rings of the coordinated ligand L are magnetically non-equivalent. Ce^{IV} oxidation of **3a** in water did not lead to any isolated Ru=O species. Presumably the low solubility of **3a** in aqueous solution complicates the synthesis. However, oxidation of **3a** or **b** in CH_2Cl_2 by 3 equiv. of MCPBA (*m*-chloroperoxybenzoic acid) at 0 °C followed by precipitation with diethyl ether gave $[Ru^{IV}L(bpy)O]^{2+}$ which was isolated as a yellowish brown PF_6^- (**4a**) or ClO_4^- salt (**4b**). Complex **4b** is stable both in the solid state and in highly purified MeCN for several hours at room temperature. In aqueous solution, it can be reduced back to **3b** by electrochemical means. The IR spectrum of **4b** is very similar to that of **3b**, with the exception of an additional ν(Ru=O) stretch at 788 cm^{-1}, indicating that the coordinated chiral imine and 2,2′-bipyridine ligands remain intact throughout the oxidation. Complexes **4a**, **b** are strong oxidants with *E*° ($Ru^{III}–Ru^{IV}$) of 0.98 V *vs.* SCE at pH = 1.1. At the same pH, the $Ru^{II}–Ru^{III}$ couple is at 0.83 V *vs.* SCE [eqns. (1) and (2)]. As with other Ru=O complexes,[5] the *E*° values of these two redox couples are pH dependent.

$$[Ru^{II}L(bpy)(OH_2)]^{2+} \rightleftharpoons [Ru^{III}L(bpy)(OH)]^{2+} + H^+ + e^- \qquad (1)$$

$$[Ru^{III}L(bpy)(OH)]^{2+} \rightleftharpoons [Ru^{IV}L(bpy)O]^{2+} + H^+ + e^- \qquad (2)$$

The structure and chirality of **3b** has been established by a X-ray crystal analysis at −80 °C.§ Fig. 1 shows a perspective view of the complex cation. The Ru atom is in a distorted octahedral geometry and the structure of L and its atomic tridentate coordination to the metal is established. The three N donor atoms of L and the Ru atom are essentially coplanar and this is similar to *trans*-$[Ru^{II}(bdmpp)(NO_2)(PMe_3)_2]ClO_4$ [bdmpp = 2,6-bis(3,5-dimethylpyrazol-1-yl)pyridine].[6] The bpy coordinates to Ru with N(6) *trans* to the oxygen atom of the coordinated water molecule. The $Ru–OH_2$ distance of 2.137(5) Å is comparable to that of 2.157(7) Å in $[Ru(terpy)(tmen)(OH_2)]^{2+}$ (terpy = 2,2′ : 6′,2″-terpyridine; tmen = *N*,*N*,*N*′,*N*′-tetramethylethylenediamine)[7] and 2.168(3) Å in $[Ru(tacn)(bpy)(OH_2)]^{2+}$ (tacn = *N*,*N*′,*N*″-trimethyl-1,4,7-triazacyclononane).[8]

Similarly to other monooxorutheium(IV) complexes, **4a**, **b** are active oxidants for alkene epoxidation (Scheme 1). Table 1 summarizes the results of stoichiometric oxidation of alkenes. In all cases, alkenes were oxidized to the corresponding epoxides with small amounts of benzaldehyde. The ruthenium product was $[Ru^{II}L(bpy)(MeCN)]^{2+}$ which was isolated as a ClO_4^- salt (**5**) and has been characterized spectroscopically. The CD spectra of **3b** and **5** are nearly identical suggesting that the coordinated ligands around the ruthenium atom remain unchanged in the epoxidation reaction. Preliminary kinetic studies revealed that oxidation of styrene by **4** in acetonitrile is

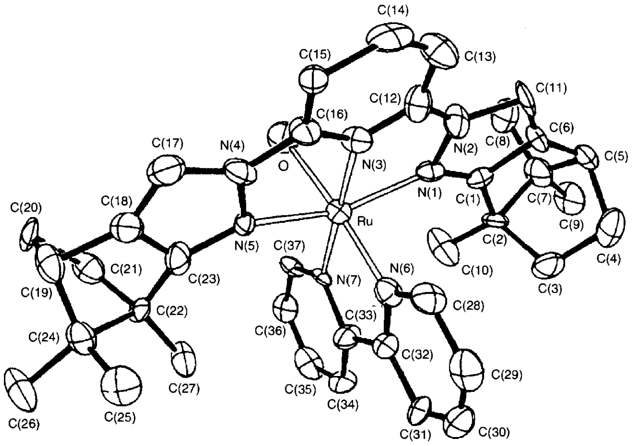

Fig. 1 A perspective drawing of one of the independent $[Ru^{II}L(bpy)(OH_2)]^{2+}$ cations. Selected bond distances (Å) and angles (°): Ru–O 2.137(5), Ru–N(3) 2.031(4), Ru–N(6) 1.985(5), Ru–N(1) 2.082(4), Ru–N(5) 2.103(4), Ru–N(7) 2.067(3), O–Ru–N(3) 87.8(2), O–Ru–N(6) 173.8(1), O–Ru–N(7) 93.1(2), O–Ru–N(1) 92.5(2), O–Ru–N(5) 85.7(2), N(1)–Ru–N(5) 156.0(1), N(3)–Ru–N(7) 178.9(2).

(3)

Scheme 1

Table 1 Asymmetric epoxidation of alkenes (100 mg) by **4b** (30 mg) in acetonitrile (10 ml) under a nitrogen atmosphere for 8 h

Substrate[a]	Products[b]	Yield[b] (%)	e.e.[c] (%)	Epoxide confign.[d]
Styrene	Styrene oxide	51	37	*R*
	Benzaldehyde	15	—	—
3-Nitrostyrene	3-Nitrostyrene oxide	70	35	*R*
4-Chlorostyrene	4-Chlorostyrene oxide	44	38	*R*
		(22)[e]	(56)[e]	*R*
	4-Chlorobenzaldehyde	12	—	—
		(8)[e]	—	—
cis-β-Methyl-styrene	*cis*-β-Methylstyrene oxide	32	30	1*R*,2*S*
	trans-β-Methylstyrene oxide	10	n.d.[f]	—
	Benzaldehyde	11	—	—

[a] Reactions were run at 25 °C unless otherwise noted. [b] Products were identified by ^{1}H NMR spectroscopy and capillary GC analysis, % yield was based on the amount of Ru^{IV}O used and was determined by GC integration against an internal standard. [c] e.e. Values were determined by GC using a chiral capillary column (J & W Scientific Cyclodex-B column, 30 m × 0.25 mm i.d., 0.25 μm film) and ^{1}H NMR in the presence of Eu(hfc)$_3$. [d] By comparison with standard. [e] Reaction was carried out at −15 °C. [f] n.d. = not determined.

first order with respect to both Ru^{IV}=O and styrene. The rate constant measured at 300 K is (1.37 ± 0.12) × 10^{-1} dm^3 mol^{-1} s^{-1} and similar reaction with 4-chlorostyrene gives a rate constant of (1.45 ± 0.13) × 10^{-1} dm^3 mol^{-1} s^{-1}. Interestingly, epoxides formed from oxidation of alkenes by **4b** at room temperature afford promising enantioselectivity (e.e. = 30–38%). At −15 °C, the e.e. of 4-chlorostyrene oxide is increased to 56%. This features the first result of asymmetric oxidation of unfunctionalized alkenes by a well characterized chiral metal–oxo complex with moderate enantioselectivity. The coordinated ligand L has chiral appendages, *i.e.* the (4*S*,7*R*)-7,8,8-trimethyl-4,5,6,7-tetrahydro-4,7-methanoindazol-2-yl group, at both sides of the pyridine ring. Studies by various groups revealed that the reaction of sterically bulky Ru^{IV}=O complexes with alkenes have large and negative $\Delta S^{\ddagger}$ values. Close association between the Ru=O moiety and C=C bond in the transition state has been proposed for the alkene epoxidation.[8,9] Thus the proximity of the chiral appendages to the Ru=O moiety is believed to impart non-bonded interactions to the approaching alkene and thereby induce enantiodifferentiation.

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Footnotes

† For correspondence regarding the crystallography.

‡ Satisfactory elemental analyses were obtained for all compounds. FAB-MS: **1** [M$^+$] 636; **2b**: [M$^+$] 721. UV–VIS [λ_{max}/nm (ε_{max}/mol^{-1} cm^{-1} dm^3)] (CH$_2$Cl$_2$): **1** 289 (27710), 325 (15020), 401 (4220), 484 (1020), 575 (830); **2** 257 (29090), 290 (72390), 327 (41280), 413 (5702), 449 (5902), 475 (6587); **3** 257 (31810), 287 (73950), 325 (45200), 446 (6861); **4** (in MeCN) 254 (32307), 286 (45590) 440sh (2070); **5** 255 (28000), 284 (60390), 317 (37720), 424 (5800). ^{1}H NMR (CD$_3$OD): **3** δ_H 0.00, 0.21 [s, 3 H each, C(10), C(27), CH$_3$], 0.10 [s, 3 H, C(25), CH$_3$], 0.65 [s, 3 H, C(8), CH$_3$], 0.78, 0.83 [s, 3 H each, C(9), C(26), CH$_3$], 2.15 (s, 3 H, CH$_3$ coordinated methanol); 0.12, 1.58 [m, 1 H each, C(3), CH*H*], 1.32, 1.82 [m, 1 H each, C(21), CH*H*], 0.91, 1.96 [m, 1 H each, C(4), CH*H*], 1.24, 2.11 [m, 1 H each, C(20), CH*H*], 2.84 [d, 2 H, J_{H-H} 3.9 Hz, C(5), C(19), CH], 8.60, 8.61 [s, 1 H each, C(11), C(17), CH], 7.98, 8.00 [d, 1 H each, J_{H-H} 8.3 Hz, C(13), C(15), CH], 8.36 [t, 1 H, J_{H-H} 8.3 Hz, C(14), CH], 7.49, 8.56, 8.82, 9.71 [d, 1 H each, bpy CH) and 7.14, 7.82, 8.09, 8.32 (m, 1 H each, bpy CH); assignments mainly based on ^{13}C–^{1}H COSY. **5** δ_H 2.47 (s, 3 H, coordinated CH$_3$CN); others are similar to **3**. ^{13}C NMR (CD$_3$OD): **3** δ 9.97, 10.54 [C(10), C(27)], 19.68, 19.81 [C(9), C(26)], 21.00, 21.82 [C(8), C(25)], 28.46, 28.59 [C(4), C(20)], 31.68 (coordinated methanol), 34.91, 35.85 [C(3), C(21)], 48.72, 48.78 [C(5), C(19)], 54.63, 54.77 [C(7), C(24)], 62.49, 62.57 [C(2), C(22)], 107.19, 107.26 [C(13), C(15)], 126.42, 126.61 [C(11), C(17)], 136.58, 136.71 [C(6), C(18)], 143.05 [C(14)], 161.10, 162.35 [C(12), C(16)], 178.05, 178.64 [C(1), C(23)], 106.88, 125.49, 126.83, 128.79, 130.18, 138.88, 140.18, 152.76, 155.41, 156.15 (bpy C).

§ *Crystal data* for **3b**·2H$_2$O, C$_{37}$H$_{43}$Cl$_2$N$_7$O$_9$Ru·2H$_2$O, M_r = 937.79, monoclinic, space group $P2_1$ (no. 4), a = 13.780(1), b = 15.836(1), c = 19.905(1) Å, β = 108.54(1)°, V = 4118(2) Å^3, Z = 4, $F(000)$ = 1936, D_c = 1.513 g cm^{-3}. Dimensions: 0.08 × 0.12 × 0.24 mm^3. Intensity data were collected at −80 °C on a Rigaku RAXIS IIC imaging-plate diffractometer using graphite-monochromated Mo-Kα radiation (λ = 0.71073 Å) from a Rigaku RU-200B rotating-anode generator powered at 50 kV and 90 mA ($2\theta_{max}$ = 55°, forty five 4° oscillation frames in the range 0–180°, exposure 14 min per frame). 15000 Independent reflections were obtained. 10399 Reflections with $|F_o| \geqslant 8\sigma(|F_o|)$ were considered observed and used in the structural analysis. The structure was solved by direct methods and refined by blocked full-matrix least squares methods using the SHELXTL-PC package. Convergence for 1045 variables by least-squares refinement of F with $w = [\sigma^2|F_o| + 0.001|F_o|^2]^{-1}$ was reached at R_F = 0.057 and R_w = 0.052 and S = 2.5 for the 10399 reflections. $(\Delta/\sigma)_{max}$ = 0.061 for atoms of the complex cation. The maximum positive and negative peaks in final difference map are +0.91 and −0.79 e Å^{-3}. Since there are four formula units in the space group $P2_1$, the asymmetric unit contains two independent sets of complex cations and perchlorate anions. Refinement is made difficult by the fact that these two sets of molecular species are closely related to each other by a noncrystallographic inversion centre. The absolute structure,[10] and hence the absolute configuration of the complex cation, were ascertained by refining a parameter η as a factor multiplying all imaginary components $\Delta f''$ of the anomalous dispersion term of the atomic scattering factors; this Rogers parameter η should ideally refine to the values of +1 or −1 for the correct and incorrect (namely wrong chirality) models, respectively.[11] In the present case the refined value of η converged to 0.356(0.037) even when its initial value was set to −1. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Information for Authors, Issue No. 1.

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