Supporting Information

Easy To Synthesize, Robust, Organo-Osmium Asymmetric Transfer Hydrogenation Catalysts

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Supporting Information

Contents

- Instrumentation
- Synthetic methods
- Catalytic reductions
- $^1$H and $^{13}$C NMR for $4a$ / $4b$ / $5a$ / $5b$
- $^1$H NMR of osmium hydride species
- Identification of dichlorido species $4a$ / $4b$
- Crystallographic data for [Os($\eta^6$-p-cymene)((R,R)-TsDPEN)] $5a$
- Crystallographic data for [Os($\eta^6$-p-cymene)((S,S)-TsDPEN)] $5b$
Instrumentation

**Nuclear magnetic resonance.** Samples of complexes 4a, 4b, 5a and 5b were prepared in CDCl₃. 5 mm NMR tubes were used to record spectra at 298 K on Bruker DPX-400 or AV-600 spectrometers. Data processing was carried out using TOPSPIN version 2.0 (Bruker UK Ltd.).

**Elemental analysis.** Elemental analysis of complexes 4a, 4b, 5a and 5b (C, H, N) was carried out by Warwick Analytical Services on an Exeter elemental analyser CE440.

**High resolution mass spectrometry.** HRMS of complexes 4a, 4b, 5a and 5b in acetonitrile were obtained using a Bruker UHR-Q-TOF MaXis. A positive ion scan range of \( m/z \) 50-3000 with a spectra rate of 1 Hz was selected. Analysis was carried out through direct infusion (2 \( \mu \)L/min) with a syringe pump, with sodium formate (10 mM) calibration. Source conditions: ESI (+); end plate offset: -500 V; capillary: -3000 V; nebulizer gas (N₂): 0.4 bar; dry gas (N₂): 4 L/min; dry temperature: 453 K; funnel RF: 200 Vpp; multiple RF: 200Vpp; quadruple low mass: 55 \( m/z \); collision energy: 5.0 eV; collision RF: 600 Vpp; ion cooler RF: 50-250 Vpp ramping; transfer time: 121 \( \mu \)s; pre-pulse storage time: 1 \( \mu \)s.

**Ultraviolet-visible spectroscopy.** The ultraviolet-visible spectra for complexes 4a, 4b, 5a and 5b in DCM (0.1 - 0.3 mM) were recorded using a Cary 300 scan spectrophotometer. Path length of cell 1 cm, range 800-200 nm, average time 0.1 s, data interval 1 nm; scan rate 600 nm/min.

**Gas chromatography.** Reduction products of 6-9: Chrompac cyclodextrin-\( \beta \)-236M-19, 50 m x 0.25 mm x 0.25 \( \mu \)m, \( P = 15 \) psi, gas H₂. Temperature varied depending on substrate. Reduction products of 10: Chrompac-chirasil-DEX CB, 25 m x 0.25 mm x 0.25 \( \mu \)m, \( T = 383 \) K, \( P = 18 \) psi, gas He.
Synthetic Methods

[Os(ƞ⁶-p-cymene)Cl₂]₂. Osmium trichloride trihydrate (1.00 g, 2.8 mmol, 2 mol equiv) was dissolved in degassed methanol (10 mL). To this was added α-phellandrene (3.8 g, 28 mmol, 20 mol equiv) with stirring. The reaction vessel was placed in a CEM Discovery-SP microwave reactor for 10 min (413 K, 150 W, 250 psi) after which a precipitate of a crystalline orange solid was observed. The solution was washed with n-pentane (3 x 10 mL) before the solid was collected, washed with additional n-pentane (3 x 10 mL) and dried with diethyl ether yielding a bright orange crystalline solid (863 mg, 1.1 mmol, 79%).

[OsCl₂(ƞ⁶-p-cymene)((H)TsDPEN)] (4a and 4b). To a stirred solution of osmium p-cymene-chlorido dimer (50 mg, 0.06 mmol, 1 mol equiv) in dry DCM (2.5 mL) was added either (1R,2R)-(H)TsDPEN (for 4a) or (1S,2S)-(H)TsDPEN (for 4b) (50 mg, 0.14 mmol, 2.05 mol equiv). The resulting yellow solution was placed in a CEM Discovery-SP microwave reactor for 10 min (393 K, 150 W, 250 psi) after which the colour changed to red. After cooling and concentration in vacuo, a large excess of hexane was added to precipitate the product as an amorphous yellow solid (88 mg, 0.12 mmol, 89%). ¹H NMR (400 MHz, CDCl₃, 25°C, TMS) δ=7.41 (d, 3J(H,H)=7.9 Hz, 2H), 7.17-7.22 (m, 2H), 7.04-7.08 (m, 2H), 6.89-6.96 (m, 3H), 6.81-6.86 (m, 3H), 6.64 (d, 3J(H,H)=7.6, 2H), 6.38 (d, 3J(H,H)=8.3 Hz, H; TsNH), 5.60 (d, 3J(H,H)=5.3 Hz, 1H; Os-ArH), 5.32-5.37 (m, 2H; Os-ArH), 5.23 (d, 3J(H,H)=5.3 Hz, 1H; Os-ArH), 5.20 (d, 3J(H,H)=11.6 Hz, 1H; NH₂), 4.50-4.58 (m, 1H; CHNH₂), 4.43-4.50 (m, 1H; CHNHTs), 4.20 (t, 3J(H,H)=10.7 Hz, 1H; CH₃), 2.59 (sept, 3J(H,H)=6.9 Hz, 1H; CH(CH₃)₂), 2.20 (s, 3H; CH₃), 2.02 (s, 3H; CH₃), 1.13 (d, 3J(H,H)=6.9 Hz, 3H; CH(CH₃)₂), 1.08 (d, 3J(H,H)=6.9 Hz, 3H; CH(CH₃)₂); ¹³C NMR (100 MHz, CDCl₃, 25°C, TMS) δ 129.3, 128.9, 128.2, 127.7, 127.4, 127.2, 72.6, 71.5, 70.9,
70.8, 65.1, 63.8, 22.6, 22.4, 21.4, 18.7; UV/Vis: \( \lambda_{\text{max}} \) 264 and 337 nm; HRMS (m/z): [M-H]- calcd. for \( \text{C}_{31}\text{H}_{35}\text{Cl}_{2}\text{N}_{2}\text{O}_{2}\text{S} \), 761.1406; found, 761.1347; [M-HCl-Cl]+ calcd. for \( \text{C}_{31}\text{H}_{35}\text{Cl}_{2}\text{N}_{2}\text{O}_{2}\text{S} \), 691.2028; found, 691.2036; analysis (calcd., found for 4a \( \text{C}_{31}\text{H}_{36}\text{Cl}_{2}\text{N}_{2}\text{O}_{2}\text{S} \)): C (48.87, 48.72), H (4.76, 4.73), N (3.68, 3.76); analysis (calcd., found for 4b \( \text{C}_{31}\text{H}_{36}\text{Cl}_{2}\text{N}_{2}\text{O}_{2}\text{S} \)): C (48.87, 48.78), H (4.76, 4.75), N (3.68, 3.74).

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[\text{Os(\eta}^6-p\text{-cymene})(\text{TsDPEN})] \text{(5a and 5b).}
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Osmium \( p \)-cymene-chlorido dimer (51.4 mg, 0.065 mmol 1 mol equiv) and either (1\( R,2R \))-\( (H)\)TsDPEN (for 5a) or (1\( S,2S \))-\( (H)\)TsDPEN (for 5b) (51.3 mg, 0.14 mmol, 2.1 mol equiv) were stirred in chloroform (5 mL) with freshly ground KOH (56.1 mg, 1 mmol, 15 mol equiv). A colour change from yellow to red was observed < 1 min. After 5 min, \( \text{H}_2\text{O} \) (5 mL) was added with stirring for a further 10 min. The organic layer was removed by syringe and concentrated in vacuo to yield a red oil, which was dissolved in the minimum amount of DCM, followed by addition of a large excess of \( n \)-hexane. Formation of red needle crystals was observed (sometimes requiring further reduction in the volume of solvent in vacuo), and larger crystals were grown by leaving the DCM/\( n \)-hexane solution in a freezer at 253 K. A significant reduction in yield was observed when the product was collected as a red solid (73 mg, 0.105 mmol, 81%). \( ^1\text{H NMR} \) (400 MHz, CDCl\(_3\), 25°C, TMS): \( \delta=7.41 \) (d, \( ^3\text{J(H,H)}=7.6 \) Hz, 2H), 7.05-7.20 (m, 10H), 6.82 (d, \( ^3\text{J(H,H)}=8.0 \) Hz, 2H), 6.80 (br s, 1H; NH), 5.79 (d, \( ^3\text{J(H,H)}=5.6 \) Hz, 1H; Os-ArH), 5.62 (d, \( ^3\text{J(H,H)}=5.6 \) Hz, 1H; Os-ArH), 5.52 (d, \( ^3\text{J(H,H)}=5.6 \) Hz, 1H; Os-ArH), 5.42 (d, \( ^3\text{J(H,H)}=5.6 \) Hz, 1H; Os-ArH), 4.42 (s, 1H; CHCHNH\(_2\)), 2.23 (s, 3H; CH\(_3\)), 2.22 (s, 3H; CH\(_3\)), 2.23 (s, 3H; CH\(_3\)), 2.22 (s, 3H; CH\(_3\)), 1.23 (d, \( ^3\text{J(H,H)}=6.9 \) Hz, 3H; \( \text{CH(CH}_3)_2 \)), 1.17 (d, \( ^3\text{J(H,H)}=6.9 \) Hz, 3H; \( \text{CH(CH}_3)_2 \)); \( ^{13}\text{C NMR} \) (100 MHz, CDCl\(_3\), 25°C, TMS) \( \delta \) 127.4, 127.0, 126.8, 126.0, 125.9, 125.9, 125.4, 81.7, 76.2, 72.4, 70.7, 70.0, 66.2, 22.5, 22.4, 20.2; UV/Vis: \( \lambda_{\text{max}} \) 260, 410 and 478 nm; HRMS (m/z): [M+H]\(^{+}\) calcd.
for C$_{31}$H$_{35}$N$_2$O$_2$OsS, 691.2; found, 691.2; analysis (calcd., found for 5a C$_{31}$H$_{34}$N$_2$O$_2$OsS): C (54.05, 53.66), H (4.97, 4.88), N (4.07, 3.95); analysis (calcd., found for 5b C$_{31}$H$_{34}$N$_2$O$_2$OsS): C (54.05, 53.71), H (4.97, 4.84), N (4.07, 4.00).

**Crystal growth for complexes 5a and 5b.** Single crystals of C$_{31}$H$_{34}$N$_2$O$_2$OsS 5a and 5b were grown from CHCl$_3$/hexane. A suitable crystal was selected in each case and mounted on a glass fibre with Fromblin oil and placed on an Oxford Diffraction Gemini diffractometer with a Ruby CCD area detector. The crystal was kept at 150(2) K during data collection. Using Olex2$^{[1]}$, the structure was solved with the ShelXS$^{[2]}$ structure solution program using Direct Methods and refined with the ShelXL$^{[2]}$ refinement package using Least Squares minimisation. Both complexes had a Flack parameter greater than 2$\sigma$ from zero however this is within an acceptable range for complexes synthesised from compounds of known chirality.
Catalytic Reductions

ATH reductions were conducted under N₂ for 24 h unless stated otherwise. Aliquots of reaction solution for analysis were placed into 1 mL EtOAc and 1 mL NaHCO₃ and the organic layer was filtered through a plug of silica. Conversion and e.e. were analysed by GC-FID.

**Asymmetric reduction of 6-10 (S/C = 100).** Pre-catalyst 4a / 4b (7.61 mg, 10 µmol, 1 mol equiv) was stirred in a 5:2 formic acid / triethylamine azeotrope (0.5 mL) for 30 min to ensure the catalyst was dissolved. A prochiral ketone (6-10) was injected (1 mmol, 100 mol equiv) and stirred.

**Asymmetric reduction of 6 (S/C = 200).** Active catalyst 5a / 5b (3.45 mg, 5 µmol, 1 mol equiv) was stirred in a 5:2 formic acid / triethylamine azeotrope (0.5 mL) for 30 min to ensure the catalyst was completely dissolved. Acetophenone 4 (120 mg) was injected (1 mmol, 200 mol equiv) and stirred.

**Racemic reduction of 7-8 with NaBH₄.** To an ice-cold solution of sodium borohydride (100 mg, 2.53 mmol, 2 mol equiv of H⁺) in ethanol (1.5 mL) was added 4'-chloro-acetophenone (0.67 mL, 5.14 mmol) or 4'-methoxy-acetophenone (771 mg, 5.14 mmol) drop-wise over 15 min. A white solid was precipitated by addition of 3 M HCl (0.5 mL). Diethyl ether (5 mL) and water (5 mL) were added and the organic layer was dried over MgSO₄. The solvent was evaporated, yielding a colourless liquid.

**Chiral GC data for reduction products from the following ketones:**

**Acetophenone (6).** 120 mg. **6** = 12.1 min, **S** = 19.0 min, **R** = 18.4 min. **T** = 388 K, **t** = 0.5 h.

**4'-chloro- (7).** 155 mg. **7** = 10.5 min, **S** = 17.1 min, **R** = 16.5 min. **T** = 423 K, **t** = 0.5 h.

**4'-methoxy- (8).** 150 mg. **8** = 35.7 min, **S** = 40.5 min, **R** = 39.0 min. **T** = 403 K, **t** = 1 h.

**α-chloro- (9).** 155 mg. **9** not recorded, **S** = 11.4 min, **R** = 11.2 min. **T** = 388 K, **t** = 0.5 h.

**Propiophenone (10).** 134 mg. **10** = 9.4 min, **S** = 26.0 min, **R** = 24.0 min. **T** = 383 K, **t** = 0.5 h.
NMR Data for complex 4a

Figure S1: $^1$H-NMR spectrum of complex 4a (400 MHz, CDCl$_3$, TMS) with key assignments.

Figure S2: $^{13}$C-NMR spectrum (dept 135, long acquisition) of complex 4a (100 MHz, CDCl$_3$, TMS).
NMR Data for complex 4b

Figure S3: $^1$H-NMR spectrum of complex 4b (400 MHz, CDCl$_3$, TMS) with key assignments.

Figure S4: $^{13}$C-NMR spectrum (dept 135, long acquisition) of complex 4b (100 MHz, CDCl$_3$, TMS).
NMR for complex 5a

Figure S5: $^1$H-NMR spectrum of complex 5a (400 MHz, CDCl$_3$, TMS) with key assignments.

Figure S6: $^{13}$C-NMR spectrum (dept 135, long acquisition) of complex 5a (100 MHz, CDCl$_3$, TMS).
**NMR for complex 5b**

*Figure S7:* $^1$H-NMR spectrum of complex 5b (400 MHz, CDCl$_3$, TMS) with key assignments.

*Figure S8:* $^{13}$C-NMR spectrum (dept 135, long acquisition) of complex 5b (100 MHz, CDCl$_3$, TMS).
'H NMR of osmium hydride species

The treatment of complex 4 with 4.0 mol equiv of triethylamine followed by the addition of 2 µL of formic acid allowed for the observation of osmium hydride resonances, observed as two singlets at -5.89 and -6.04 ppm, each having $^{187}$Os satellites ($^1J(^{187}\text{Os},^1\text{H}) = 44$ Hz). Over a period of 30 min, the ratio between the resonances decreased from 3:1 to 1.2:1; a similar observation has been made in the case of the analogous Ru$^{II}$ complexes.$^3$

Figure S9: 600 MHz $^1$H-NMR spectrum showing Os-H formation as two singlets with the ratio changing over time: initially 3:1 (top) and 1.2:1 after 30 min (bottom).
Identification of Dichlorido Species 4a / 4b

Evidence for the characterisation of 4a / 4b as species containing two chlorido ligands was obtained, revealing the novel monodentate-(H)TsDPEN complex that differs from Noyori-type ruthenium catalysts.

Infra-red spectroscopy

TsN-H bond stretch absorbance remains at 2859 cm\(^{-1}\), whilst terminal amine N-H stretches are shifted from 3344 and 3281 cm\(^{-1}\) in the free ligand to 3078 and 2953 cm\(^{-1}\) in the complex.

Mass spectrometry

Dichlorido species 4 identified by high resolution MS (Bruker MaXis) with samples of the complex in acetonitrile. The mass is consistent with synthesis in the absence of base.

Figure S10: HRMS of 4a-H (upper) and simulated spectrum of C\(_{31}\)H\(_{36}\)N\(_2\)O\(_2\)OsCl\(_2\) (lower).
**Figure S11:** HRMS of [4a-HCl-Cl]⁺ (top) and simulated spectrum of C₃₁H₃₅N₂O₂OsS (bottom).
Crystallographic data for [Os(ƞ₆-p-cymene)((R,R)-TsDPEN)] 5a - CCDC 1035611

Figure S12: X-ray crystal structure of 5a with atom labels. Thermal ellipsoids are drawn at the 50% probability level. The asymmetric unit contains the complex, there are 4 complexes in the unit cell. The hydrogen on N12 was located in a difference map. It was allowed to refine freely but given a U_{iso} 1.5 times U_{equiv} of the parent nitrogen. The Flack parameter was more than 2 sigma from zero, but is from a known chiral starting material so is within acceptable limits.

Crystal Data for C₃₁H₃₄N₂O₂OsS (M=688.86 g/mol): orthorhombic, space group P2₁2₁2₁ (no. 19), a = 10.6100(3) Å, b = 13.8464(3) Å, c = 18.9830(5) Å, V = 2788.79(11) Å³, Z = 4, T = 150(2) K, μ(MoKα) = 4.678 mm⁻¹, Dcalc = 1.641 g/cm³, 33345 reflections measured (4.836° ≤ 2θ ≤ 61.698°), 8053 unique (R_{int} = 0.0557, R_{sigma} = 0.0502) which were used in all calculations. The final R₁ was 0.0333 (I > 2σ(I)) and wR₂ was 0.0927 (all data).

Flack x: 0.023(5) (Shelx); Hooft y: 0.039(5) (Olex2)

Selected distances (Å) and angles (°): Os-N12 1.916(6), Os-N9 2.046(6), N12-H12 0.96(11); N12-Os-N9 78.3(3), Os-N12-C11 121.6(5), Os-N9-C10 115.9(4).
Crystallographic data for [Os(η⁶-p-cymene)((S,S)-TsDPEN)] 5b - CCDC 1035612

**Figure S13:** X-ray crystal structure of 5b with atom labelling. Thermal ellipsoids are drawn at 50% probability level. The asymmetric unit contains the complex. There are four complexes in the unit cell. The hydrogen was located on N12 and refined with a DFIX restraint and given a U_{iso} 1.5 times the U_{equiv} of N12. The Flack parameter was more than 2 sigma from zero, but is from a known chiral starting material so is within acceptable limits (similarly for 5a).

**Crystal Data** for C₃₁H₃₄N₂O₂OsS (M=688.86 g/mol): orthorhombic, space group P2₁2₁2₁ (no. 19), a = 10.61241(15) Å, b = 13.8542(2) Å, c = 18.9999(3) Å, V = 2793.49(8) Å³, Z = 4, T = 150(2) K, μ(MoKα) = 4.670 mm⁻¹, D_{calc} = 1.638 g/cm³, 48265 reflections measured (4.836° ≤ 2Θ ≤ 67.25°), 10419 unique (R_{int} = 0.0258, R_{sigma} = 0.0182) which were used in all calculations. The final R₁ was 0.0184 (I > 2σ(I)) and wR₂ was 0.0774 (all data).

Flack x: 0.015(2); Hooft y: 0.0070(15) (Olex2)

Selected distances (Å) and angles (°): Os-N12 1.914(3), Os-N9 2.047(4), N12-H12 0.96(3); N12-Os-N9 78.27(16), Os-N12-C11 122.1(3), Os-N9-C10 115.4(2).
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