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Research paper

Asymmetric ruthenium tricarbonyl cyclopentadienone complexes; synthesis and application to asymmetric hydrogenation of ketones

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ABSTRACT

A series of enantiomerically-pure ruthenium tricarbonyl cyclopentadienone complexes were prepared via the cyclisation of C2-symmetric dialkynes with $Ru_3(CO)_{12}$. Four complexes were characterised by X-ray crystallography and a hydride derivative of one of these was characterised. The complexes were tested in the asymmetric hydrogenation and transfer hydrogenation of acetophenone. Whilst the catalysts were active, acetophenone was reduced in low ee, however a reduction product of up to 46% ee could be obtained when a mild base ($^{i}Pr_2NEt$ or pyridine) was added to the reaction.

1. Introduction

Metal complexes of cyclopentadienones, notably ruthenium [1] and iron [2] derivatives of general structure **1** and **2**, have been applied as catalysts in hydrogen transfer reactions [3], operating via their metal hydride derivatives [4]. Asymmetric versions of the ligands have also been reported to be effective however derivatives which deliver products in high ee remain elusive. In recent work, we [5] and others [6], have reported asymmetric iron cyclopentadienone complexes **3–6** and have found that these will reduce ketones in up to 77% ee [6c]. Although iron complexes are desirable due to their improved environmental properties compared to precious metal group catalysts, ruthenium derivatives are generally more active and stable under catalytic conditions, and can be used at lower loadings [5a]. In addition, very few examples of asymmetric ruthenium cyclopentadienone complexes have been reported, with field seemingly restricted to examples **7** [5a], **8** [7] and **9** [8], all of which rely on planar chirality to induce asymmetry in the reactions which they catalyse. In our studies [5a], complexes of type **7** achieved asymmetric transfer hydrogenation of acetophenone in no higher than 17% ee, whereas complex **8** reduced acetophenone in up to 21% ee under a 35 atm pressure of hydrogen gas [7]. Complex **9** catalysed the transfer hydrogenation of 1,1,1-trifluoroacetophenone in up to 56% ee and an imine in up to 64% ee [8]. During their catalytic cycles, the iron and ruthenium complex form active hydride species of general structures **10** (monomer) and **11** (dimer) respectively. In order to provide a comparison between iron and ruthenium systems, we have now prepared a series of ruthenium analogues of our earlier iron complexes **6** and have tested them as catalysts for ketone reduction (Fig. 1).

2. Results and discussion

The synthesis of four asymmetric ruthenium tricarbonyl cyclopentadienone complexes **13a-13d** was achieved through intramolecular cyclisation of dialkoxy dialkynes precursors using $Ru_3(CO)_{12}$ following an established procedure. Whilst dialkynes **12a-12c** are known, compound **12d**, containing methoxy substituents, is novel and was prepared via methylation of the known diol **12a**. The isolation of the side product **14** from the synthesis of **13a**, where a shorter reaction time was used (2 days instead of 5 days), indicates that this is likely intermediate in its formation (Scheme 1).

The reactions worked efficiently and delivered products in good yields and in crystalline form, allowing full characterisation by spectroscopic methods. X-ray crystallographic structures were obtained of all the ruthenium cyclopentadienone complexes and of the diruthenium complex **14** and these are shown in Fig. 2 (Full details in the Supporting Information). In all cases the anticipated ruthenium tricarbonyl structure was present, with the phenyl groups flanking the central C═O in a twisted orientation, presumably influenced by the adjacent alkoxy groups. The structures were similar to those reported for the iron analogues [5b,c]. An X-ray crystallographic structure of the diruthenium complex **14** was also obtained, which confirmed its interesting symmetric structure in which each ruthenium was bonded to three carbon monoxide ligands (Fig. 2 b).

A hydride complex **15** was formed from **13b** upon treatment with the mild base $NaHCO_3$, and this is likely to be an intermediate in the asymmetric reductions (Fig. 3). This was sufficiently stable to be isolated and was characterised by NMR spectroscopy.

Each of the new complexes **13a-13d** was tested as a catalyst for asymmetric hydrogenation of acetophenone (Table 1) using the

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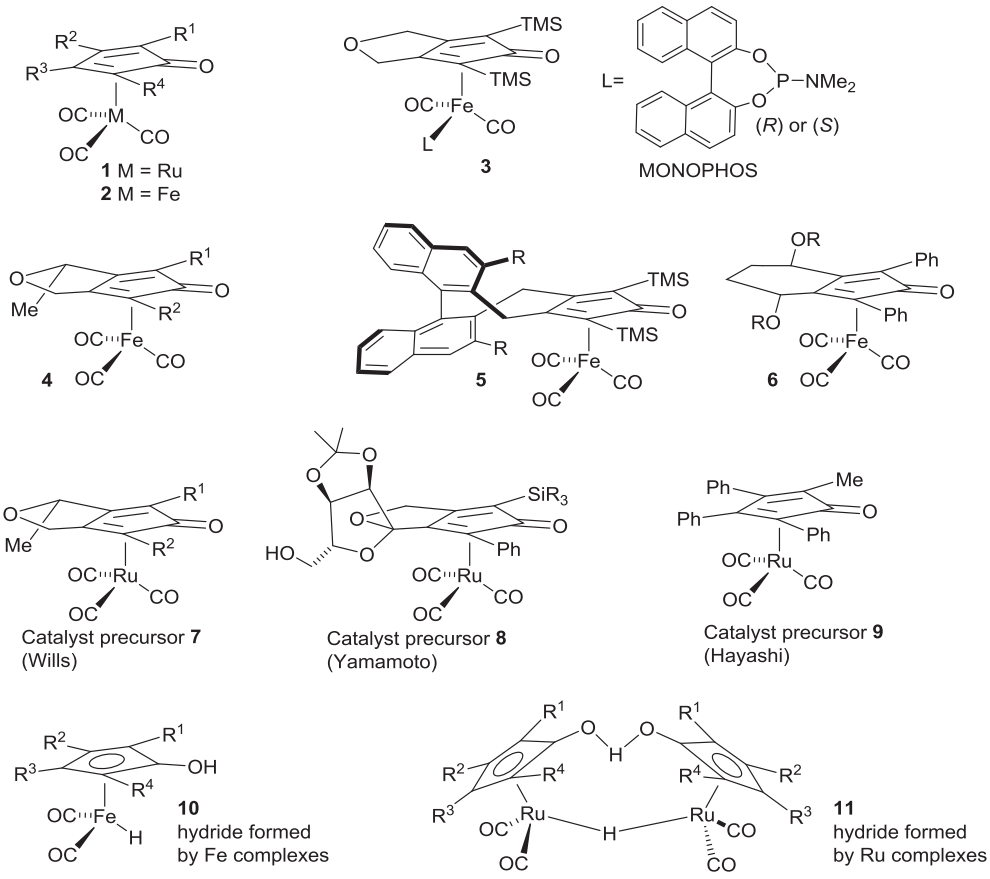
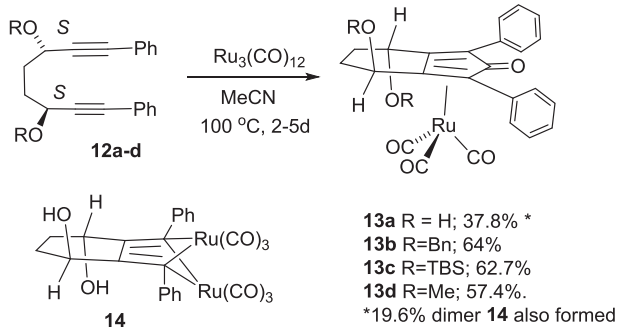


Fig. 1. Reported asymmetric and non-asymmetric catalysts based on iron- and ruthenium tricarbonyl cyclopentadienone structures, and their active hydride derivatives.



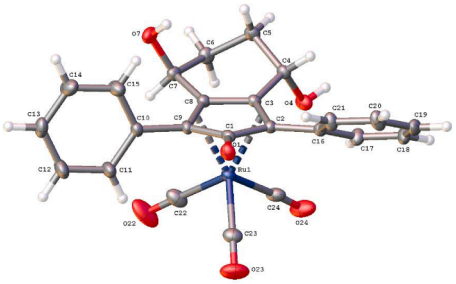
Scheme 1. Route to Ru complexes **13a-13d** prepared in this project, and diruthenium complex **14** also formed during preparation of **13a**.

conditions we had previously reported, and a range of representative results are reported in Table 1. A detailed Table featuring the results of all our tests is reported in the Supporting Information. Using **13a** as the catalyst, the addition of TMAO as an activator was required for full conversion within 18 h at 80 °C, although good conversion was obtained without the activator. The product was essentially racemic however. The use of 5% K_2CO_3 in place of TMAO gave lower conversion, and the ee remained low. A similar pattern of results was obtained using catalyst **13b**, which was slightly less reactive than **13a**. Pyridine N-oxide was also shown to be an effective initiator for this catalyst, however TMAO was retained for future tests as it is easier to remove from the reaction mixture after use. Catalysts **13c** and **13d** also gave full conversions under our standard conditions, however catalyst **13d** gave full conversion to product both in the absence of TMAO and if an excess of this was used, or if 5% K_2CO_3 was used. However the different reaction conditions had no effect on the ee of the product.

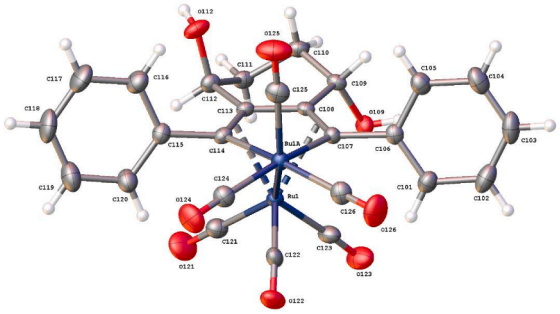
The effect of the addition of a range of additives to the reductions was studied, using the benzyloxy catalyst **13b** throughout for consistency (Table 2). Triphenylphosphine reduced the overall conversion and had little effect on the product ee. 2-Picoline, lutidine, and $^{i}Pr_2NEt$ additives increased the product ees, with a product of 45% ee being obtained with 10 mol% of $^{i}Pr_2NEt$, which is one of the highest recorded asymmetric inductions we have achieved with this class of catalyst. However full conversions were not achieved, and more than 10 mol% of the amine reduced the conversions notably. The addition of triethylamine at up to 10% did not reduce the conversion but the ee dropped to 0%, whilst dimethyl aniline had little effect on the conversion or ee. The addition of 2,2′-dipyridine as an additive was also investigated but gave product of just up to 4.8% ee, although with 97% conversion (see supporting information).

The addition of pyridine as an additive was investigated in more detail with catalysts **13b** (Table 3), **13c** (Table 4) and **13d** (Table 5). Using catalyst **13b** (Table 3) the effect of the relative amounts of TMAO and pyridine was studied, with a steady increase in ee observed as both were increased, with > 99% conversion maintained, and an ee of 38.2% delivered using 5 mol%. The ee increased further (up to 46%) when 10 mol% of each additive was added however the conversion dropped. The reaction was carried out at 40 °C however both the conversion and ee decreased. A similar pattern of result was observed for catalyst **13c**, with the use of 50% of both TMAO and pyridine reducing the reaction efficiency (Table 4). The effect of the addition of pyridine to catalyst **13a** was also investigated; although the ee was increased to 10.8% using 10% TMAO and 10% pyridine, the yield was slightly reduced (see Supporting information).

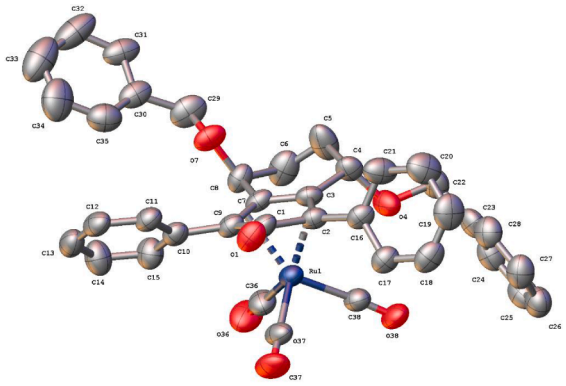
In the case of catalyst **13d**, a similar pattern of results was observed, with slightly improved product ees observed using 5 mol% TMAO and



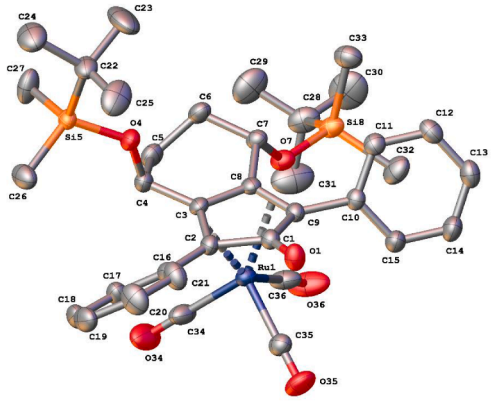
a) X-ray crystallographic structure of **13a.**



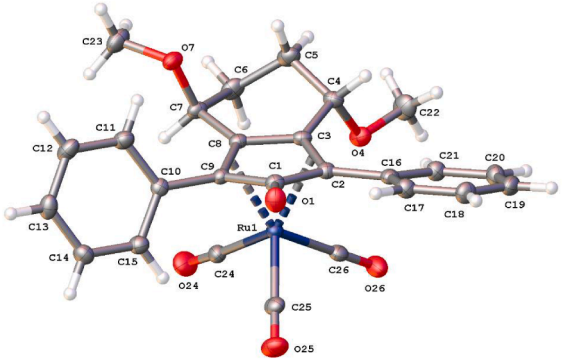
b) X-ray crystallographic structure of **14.**



c) X-ray crystallographic structure of **13b.**



d) X-ray crystallographic structure of **13c.**



e) X-ray crystallographic structure of **13d.**

Fig. 2. X-ray crystallographic structures of ruthenium complexes prepared in this project.

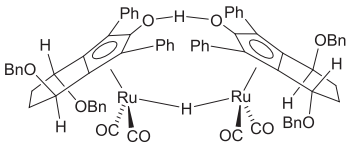


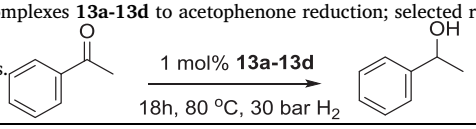
Fig. 3. Hydride complex **15** formed from complex **13b**.

pyridine (Table 5). The opportunity was taken to examine the effect of alternative solvents, with several found to be compatible with the conditions. Using DMSO, the configuration changed sharply to 33.2% (*S*), although the conversion was low.

3. Conclusions

In conclusion, we have prepared a series of asymmetric ruthenium tricarbonyl cyclopentadienone complexes using an efficient intramolecular cyclisation reaction with $Ru_3(CO)_{12}$. These are stable complexes which are readily isolated and purified, and all were characterised by NMR, HRMS and X-ray crystallography. All of the complexes proved to be highly effective in the asymmetric hydrogenation of acetophenone, as a prototype substrate which allows comparisons to be made with other catalysts. Full conversion to the alcohol product was possible in most cases, and provided that TMAO activator was added, although the product ees were low. A study of additives revealed that the addition of pyridine could raise the product ee to 38.2% whilst maintaining full conversion. The use of 10 mol% $^{i}Pr_2NEt$ as an additive raised the ee to 46% without a reduction in conversion, which is one of the highest ees we have obtained for acetophenone reduction using this class of ruthenium-based catalysts. The basic additives may be forming modified complexes or influencing the reaction in other ways, and this

Table 1
Application of complexes **13a-13d** to acetophenone reduction; selected results without additives.



Entry	Catalyst	TMAO/%	Experimental Details	Conv./%	Ee/%
1	**13a**	1	IPA/H_2O	> 99	2.4 (*R*)
2	**13a**	0	IPA/ H_2O	83.1	2.1 (*S*)
3	**13a**	0	5% K_2CO_3 IPA/H_2O	85.9	7.0 (*R*)
4	**13b**	1	IPA/ H_2O	82.4	2.2 (*S*)
5	**13b**	0	IPA/ H_2O	65.4	3.6 (*S*)
6	**13b**	0	5% K_2CO_3, IPA/H_2O	78.3	2.6 (*S*)
7	**13b**	5[a]	IPA/ H_2O	> 99	4.8 (*S*)
8	**13b**	10[a]	IPA/ H_2O	95.8	4.4 (*S*)
9	**13c**	1	IPA/ H_2O	> 99	8.8 (*R*)
10	**13d**	1	IPA/H_2O	> 99	3.8 (*S*)
11	**13d**	2	IPA/H_2O	> 99	3.6 (*S*)
12	**13d**	3	IPA/H_2O	> 99	3.8 (*S*)
13	**13d**	5	IPA/H_2O	> 99	3.4 (*S*)
14	**13d**	0	IPA/H_2O	> 99	4.2 (*S*)
15	**13d**	0	5% K_2CO_3, IPA/H_2O	> 99	2.4 (*S*)

[a] Pyridine N-oxide was used in place of TMAO.

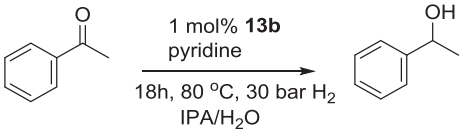
is currently under investigation.

4. Experimental section.

4.1. General experimental

General; Solvents and reagents for the synthesis of complexes and catalytic reactions were degassed prior to use and all reactions were carried out under either a nitrogen or argon atmosphere. All heated experiments were conducted using thermostatically controlled oil baths. Reactions were monitored by TLC using aluminum backed silica gel 60 (F254) plates, visualized using UV 254 nm and phosphomolybdic acid (PMA), potassium permanganate or vanillin dips as appropriate. Flash column chromatography was carried out routinely using 60 μm silica gel. Reagents were used as received from commercial sources unless otherwise stated. ^{1}H NMR spectra were recorded on a Bruker DPX (300, 400 or 500 MHz) spectrometer. Chemical shifts are reported in δ units, parts per million relative to the singlet at 7.26 ppm for chloroform and 0.00 ppm for TMS. Coupling constants (J) are measured in Hertz. IR spectra were recorded on a Perkin-Elmer Spectrum One FT-

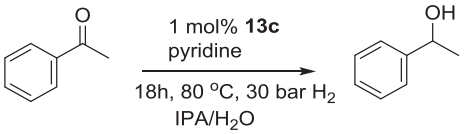
Table 3
Effect of pyridine on asymmetric hydrogenation of acetophenone using complex **13b**.



Entry	TMAO/%	Pyridine/%	Conv/%	Ee/%
1	1	1	> 99	1.6 S
2	2	1	> 99	7.0 (*R*)
3	1	2	> 99	5.0 (*R*)
4	2	2	> 99	11.0 (*R*)
5	3	2	> 99	17.0 (*R*)
6	3	3	> 99	27.8 (*R*)
7	3	5	> 99	32.2 (*R*)
8	5	3	94	33.8 (*R*)
9	5	5	> 99	38.2 (*R*)
10	5	10	89.2	41.6 (*R*)
11	10	10	66.0	46.0 (*R*)
12	10[a]	10	32.2	28.2 (*R*)

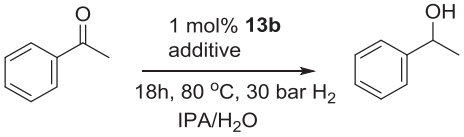
a. The reaction was carried out at 40 °C.

Table 4
Effect of pyridine on asymmetric hydrogenation of acetophenone using complex **13c.**



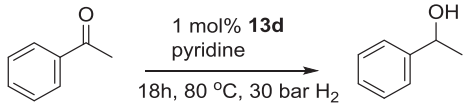
Entry	TMAO/%	Pyridine/%	Conv/%	Ee/%
1	5	5	> 99	18.2 (*R*)
2	10	10	> 99	20.8 (*R*)
3	50	50	53.9	12.0 (*R*)

Table 2
Effect of additives on asymmetric hydrogenation of acetophenone using complex **13b**.



Additive:		PPh_3		2-picoline		Lutidine	
TMAO/%	Additive/%	Conv/%	Ee/%	Conv/%	Ee/%	Conv/%	Ee/%
5	5	37.7	8.4 (*R*)	> 99	2.2 (*R*)	> 99	4.0 (*S*)
10	10	55.9	7.6 (*R*)	91.7	14.0 (*R*)	65.3	7.2 (*R*)
50	50	58.5	10.8 (*R*)	74.6	27.6 (*R*)	85.6	19.4 (*R*)
Additive:		^{i}Pr_2NEt		Et_3N		Dimethylaniline	
TMAO/%	Additive/%	Conv/%	Ee/%	Conv/%	Ee/%	Conv/%	Ee/%
5	5	> 99	10.6 (*R*)	> 99	3.6 (*S*)	99	42.0 (*S*)
10	10	> 99	45.0 (*R*)	> 99	0	99	5.6 (*S*)
50	50	87.6	46.2 (*R*)	–	–	99	11.0 (*S*)
100	100	58.9	36.2 (*R*)	–	–	–	–

Table 5
Effect of pyridine on asymmetric hydrogenation of acetophenone using complex **13d**.



Entry	TMAO/%	Pyridine/%	Conv/%	Ee/%	Solvent
1	5	5	> 99	15.4 (*R*)	IPA/H_2O
2	5	5	> 99	17.2 (*R*)	IPA/H_2O
3	50	50	85.6	22.4 (*R*)	IPA/H_2O
4	10	10	> 99	28.6 (*R*)	Toluene
5	10	10	> 99	20.2 (*R*)	EtOAc
6	10	10	> 99	22.0 (*R*)	THF
7	10	10	> 99	17.4 (*R*)	MeCN
8	10	10	19.1	33.2 (*S*)	DMSO
9	10	10	> 99	15.2 (*R*)	DMF

IR Golden Gate. Mass spectra were recorded on a Bruker Esquire2000 or a Bruker MicroTOF mass spectrometer. Melting points were recorded on a Stuart Scientific SMP 1 instrument and are uncorrected. GC analysis was performed using a Hewlett Packard 5890. Dry solvents were purchased and used as received. Compounds 12a-12c were prepared as reported in literature [5b,c].

4.1.1. Tricarbonyl-(4S,7S)-4,7-dihydroxy-1,3-diphenyl-4,5,6,7-tetrahydro-2H-inden-2-one ruthenium 13a and diruthenium complex 14

In an ACE pressure tube under a nitrogen atmosphere (3S,6S)-1,8-diphenylocta-1,7-diyne-3,6-diol **12a** (681 mg, 2.35 mmol) was dissolved in anhydrous acetonitrile (12 cm^3) and nitrogen was bubbled for 15 min. $Ru_3(CO)_{12}$ (500 mg, 0.78 mmol) was added, the pressure tube was sealed and the mixture was heated at 100 °C for 2 days. The mixture was cooled to room temperature and the pressure tube was carefully opened into the fumehood. Then the volatiles were removed and the product was purified by flash chromatography on silica gel (eluent: Pentane/EtOAc = 4:1 to 2:3) to give tricarbonyl-(4S,7S)-4,7-dihydroxy-1,3-diphenyl-4,5,6,7-tetrahydro-2H-inden-2-one ruthenium **13a** (446 mg, 0.88 mmol, yield: 37.8%) as yellow solid and diruthenium complex **14** (304 mg, 0.46 mmol, yield: 39.2%) as yellow solid. Crystals of **13a** for X-ray crystallography were grown by slow diffusion of hexane into an acetone solution of the compound. Crystals of **14** for X-ray crystallography were grown by leaving the initially oily product solidify in the air.

4.1.2. Tricarbonyl-(4S,7S)-4,7-dihydroxy-1,3-diphenyl-4,5,6,7-tetrahydro-2H-inden-2-one ruthenium 13a

TLC: silica gel, 40:60 hexane:EtOAc, Rf ca 0.25. m.p. 161.3 °C dec. $[\alpha]_D^{25}$ −30.1 (*c* 0.13, $CHCl_3$). $IR_{(neat)}$ 3384 (broad), 3256 (broad), 3063, 2957, 2942, 2927, 2910, 2079, 2022, 2009, 1605, 1583, 1500, 1445, 1434, 1399, 1334, 1278, 1214 cm^{-1}. δ_H (500 MHz, DMSO-d_6) 7.78–7.83 (2H, m, Ar*H*), 7.74–7.78 (2H, m, Ar*H*), 7.34–7.41 (4H, m, Ar*H*), 7.26–7.33 (2H, m, Ar*H*), 5.68 (1H, d, *J* = 4.1 Hz, O*H*), 5.55 (1H, d, *J* = 6.0 Hz, O*H*), 4.65 (1H, dt, *J* = 6.1, 3.2 Hz, C*H*OH), 4.38 (1H, m, C*H*OH), 2.25 (1H, tt, *J* = 14.1, 3.6 Hz, CH*H*), 2.03–2.14 (1H, m, CH*H*), 1.68–1.77 (1H, m, C*H*H), 1.60 (1H, m, C*H*H). δ_C (125 MHz, DMSO-d_6) 194.8 (C), 173.5 (C), 132.7 (C), 132.1 (C), 130.8 (CH), 130.3 (CH), 127.95 (CH), 127.92 (CH), 127.11 (CH), 127.07 (CH), 109.2 (C), 104.8 (C), 80.2 (C), 79.0 (C), 61.1 (CH), 57.6 (CH), 26.8 (CH_2), 26.1 (CH_2). *m/z* (ESI) $[M + H]^+$ 505.0; $[M + Na]^+$ 527.0. HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{24}H_{18}{}^{102}RuO_6Na$ 527.0046; Found 521.0051.

4.1.3. Diruthenium complex 14

mp 74.2 °C decomp; m.p. 74.2 °C dec. $[\alpha]_D^{25}$ −60.9 (*c* 0.11, $CHCl_3$). $IR_{(neat)}$ 3528 (broad), 3403 (broad), 2926, 2862 2078, 2042, 1687, 1634, 1592, 1570, 1489, 1438, 1389, 1335, 1245 cm^{-1}. δ_H (500 MHz, $CDCl_3$) 7.19–7.34 (6H, m, Ar*H*), 7.12–7.18 (2H, m, Ar*H*), 6.81 (2H, dd, *J* = 16.3, 7.2 Hz, Ar*H*), 4.88–4.96 (1H, m, C*H*OH), 4.35 (1H, q, *J* = 3.4 Hz, C*H*OH), 2.32–2.46 (1H, m, C*H*H), 2.16 (1H, tt, *J* = 13.5, 3.3 Hz, CHH), 2.07 (1H, d, *J* = 3.4 Hz, OH), 1.67–1.86 (3H, m, CH_2 and OH). δ_C (125 MHz, $CDCl_3$) 198.9, 195.5, 193.0, 192.6, 167.7, 162.1, 148.4, 162.1, 148.4, 147.7, 133.7, 130.7, 129.22, 129.17, 129.0, 128.7, 128.54, 128.51, 128.4, 128.3, 128.1, 126.3, 126.2, 126.0, 123.8, 65.4, 60.9, 26.4, 26.2.

4.1.4. Tricarbonyl-(4S,7S)-4,7-bis(benzyloxy)-1,3-diphenyl-4,5,6,7-tetrahydro-2H-inden-2-one ruthenium 13b

In an ACE pressure tube under a nitrogen atmosphere (3*S*,6*S*)-(3,6-bis(benzyloxy)octa-1,7-diyne-1,8-diyl)dibenzene **12b** (1.10 g, 2.34 mmol) was dissolved in anhydrous acetonitrile (12 cm^3) and nitrogen was bubbled for 15 min. $Ru_3(CO)_{12}$ (500 mg, 0.78 mmol) was added, the pressure tube was sealed and the mixture was heated at 100 °C for 5 days. The mixture was cooled to room temperature and the pressure tube was carefully opened into the fumehood. Then the volatiles were removed and the product was purified by flash chromatography on silica gel (eluent: Hexane to Hexane/EtOAc = 7:3) to give tricarbonyl-(4*S*,7*S*)-4,7-bis(benzyloxy)-1,3-diphenyl-4,5,6,7-tetrahydro-2*H*-inden-2-one ruthenium **13b** (1.03 g, 1.51 mmol, yield: 64.5%) as yellow solid. Crystals for X-ray crystallography were grown by slow diffusion of hexane into an acetone solution of the compound. TLC: silica gel, 70:30 hexane:EtOAc, Rf ca 0.2. m.p. 163.3–165.5 °C. $[\alpha]_D^{25}$ + 50.9 (*c* 0.11, $CHCl_3$). $IR_{(neat)}$ 3058, 3032, 2949, 2925, 2861, 2082, 2029, 1991, 1634, 1600, 1498, 1444, 1363, 1324, 1213 cm^{-1}. δ_H (500 MHz, $CDCl_3$) 7.61–7.70 (4H, m, Ar*H*), 7.27–7.42 (8H, m, Ar*H*), 7.23–7.27 (2H, m, Ar*H*), 7.09–7.17 (2H, m, Ar*H*), 6.90–6.96 (2H, m, Ar*H*), 4.61 (1H, t, *J* = 2.8 Hz, C*H*OR), 4.47 (1H, d, *J* = 10.7 Hz, CH*H*OR), 4.30 (2H, dd, *J* = 10.5, 6.4 Hz, CH_2OR), 4.14–4.18 (1H, m, CHOR), 4.04 (1H, d, *J* = 10.4 Hz, CHHOR), 1.96–2.20 (4H, m, CH_2). δ_C (125 MHz, $CDCl_3$) 194.0 (C), 174.4 (C), 137.1 (C), 136.9 (C), 131.8 (C), 131.6 (C), 130.84 (CH), 130.75 (CH), 128.6 (CH), 128.38 (CH), 128.34 (CH), 128.27 (CH), 128.26 (CH), 128.0 (CH), 127.94 (CH), 127.90 (CH), 127.58 (CH), 127.55 (CH), 105.5 (C), 103.0 (C), 82.1 (C), 81.1 (C), 72.4 (CH_2), 71.8 (CH_2), 69.8 (CH), 66.7 (CH), 21.6 (CH_2), 21.5 (CH_2). *m/z* (ESI) $[M + H]^+$ 685.1; $[M + Na]^+$ 707.1. HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{38}H_{30}O_6{}^{102}RuNa$ 707.0989; Found 707.0971.

In addition, a further fraction containing 204 mg of what was suspected to be the corresponding diruthenium complex was isolated prior to the main product (TLC; 70:30 hexane:EtOAc, Rf ca 0.80). However this was not full characterised.

4.1.5. Hydride 15

Ruthenium complex **13b** (diOBn) (250 mg, 0.365 mmol), was dissolved in acetone (20 mL) and an aqueous solution of $NaHCO_3$ (8 mL) was added. The mixture was degassed by bubbling nitrogen through it for 30 min. After this time, an aqueous solution of NH_4Cl (40 mL) was added and the mixture was extracted with DCM (3 × 50 mL). The combined DCM extracts were dried over $MgSO_4$, filtered and the solvent removed. The crude product was columned on silica gel (hexane/EtOAc 80:20–60:40) to give **15** (202 mg, 0.154 mmol, 84.3%) as a yellow solid. $[\alpha]_D^{25}$ + 80.5 (*c* 0.09, $CHCl_3$). Mp 107.3C dec $IR_{(neat)}$ 3055, 3028, 2928, 2859, 2036, 2013, 1958, 1602, 1578, 1527, 1500, 1452, 1439, 1413, 1389, 1336. δ_H (500 MHz, $CDCl_3$)7.06–7.32 (36H, m, Ar*H*), 6.61–6.75 (4H, m, Ar*H*), 4.54 (2H, t, *J* = 2.9, C*H*), 4.35 (2H, d, *J* = 11.0 Hz, CH_2), 4.26 (2H, d, *J* = 11.0 Hz, CH_2), 4.14 (2H, d, *J* = 10.1 Hz, CH_2), 3.86–3.90 (2H, m, CH), 3.83 (2H, d, *J* = 10.1 Hz, CH_2), −18.78 (1H, s, RuH), OHO not determined. δ_C (125 MHz, $CDCl_3$) 201.5 (C), 198.7 (C), 156.1 (C), 137.7(C), 137.3 (C), 131.1 (CH), 131.0 (C), 130.8 (CH), 130.5 (C), 128.4 (CH), 128.2 (CH), 128.12 (CH), 128.10 (CH), 128.07 (CH), 127.8 (CH), 127.7 (CH), 127.6 (CH), 126.8 (CH), 100.1 (C), 97.3 (C), 86.5 (C).

4.1.6. Tricarbonyl-(4S,7S)-4,7-bis((tert-butyldimethylsilyl)oxy)-1,3-diphenyl-4,5,6,7-tetrahydro-2H-inden-2-one ruthenium 13c

In an ACE pressure tube under a nitrogen atmosphere (5*S*,8*S*)-2,2,3,3,10,10,11,11-octamethyl-5,8-bis(phenylethynyl)-4,9-dioxa-3,10-disiladodecane **12c** (1.22 g, 2.35 mmol) was dissolved in anhydrous acetonitrile (12 cm^3) and nitrogen was bubbled for 15 min. $Ru_3(CO)_{12}$ (500 mg, 0.78 mmol) was added, the pressure tube was sealed and the mixture was heated at 100 °C for 5 days. The mixture was cooled to room temperature and the pressure tube was carefully opened into the fumehood. Then the volatiles were removed and the product was purified by flash chromatography on silica gel (eluent: Hexane to Hexane/EtOAc = 1:4) to give tricarbonyl-(4*S*,7*S*)-4,7-bis((*tert*-butyldimethylsilyl)oxy)-1,3-diphenyl-4,5,6,7-tetrahydro-2*H*-inden-2-one ruthenium **13c** (1.08 g, 1.47 mmol, yield: 62.9%) as yellow solid. Crystals for X-ray crystallography were grown by slow diffusion of hexane into an acetone solution of the compound. TLC details: silica gel, hexane:EtOAc 80:20, Rf 0.25, uv/red spot. m.p. 182.8–184.9 °C. $[\alpha]_D^{27}$ −61.1 (*c* 0.10, $CHCl_3$). $IR_{(neat)}$ 3052, 2953, 2929, 2885, 2855, 2079, 2011, 1638, 1603, 1501, 1470, 1436, 1408, 1388, 1361, 1253, 1214 cm^{-1}. δ_H (500 MHz, $CDCl_3$) 7.51–7.60 (4H, m, Ar*H*), 7.39 (2H, t, *J* = 7.5 Hz, Ar*H*), 7.29–7.36 (3H, m, Ar*H*), 7.24–7.29 (1H, m, Ar*H*), 4.94 (1H, t, *J* = 2.9 Hz, C*H*OR), 4.71 (1H, dd, *J* = 4.3, 1.7 Hz, C*H*OR), 2.25–2.36 (1H, m, C*H*H), 2.17 (1H, tt, *J* = 13.4, 2.5 Hz, C*H*H), 1.74–1.81 (1H, m, CH*H*), 1.66–1.74 (1H, m, CH*H*), 0.81 (9H, s, CH_3), 0.71 (9H, s, CH_3), −0.11 (3H, s, CH_3), −0.42 (3H, s, CH_3), −0.60 (3H, s, CH_3). δ_C (125 MHz, $CDCl_3$) 194.3 (C), 175.2 (C), 131.7 (CH), 131.6 (C), 131.5 (C), 130.7 (CH), 128.5 (CH), 128.3 (CH), 127.7 (CH), 127.5 (CH), 106.97 (C), 106.95 (C), 82.6 (C), 80.0 (C), 62.9 (CH), 60.8 (CH), 27.6 (CH_2), 26.3 (CH_2), 26.2 (CH_3), 25.7 (CH_3), 18.2 (C), 18.0 (C), −4.3 (CH_3), −4.6 (CH_3), −5.3 (CH_3), −5.9 (CH_3). *m/z* (ESI) $[M + H]^+$ 733.2; $[M + Na]^+$ 755.1. HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{26}H_{22}FeO_8Na$ 755.1778; Found 755.1776.

4.1.7. ((3S,6S)-3,6-Dimethoxyocta-1,7-diyne-1,8-diyl)dibenzene 12d

Diol **12a** (900 mg, 3.10 mmol) was dissolved in DMF (10 mL) and the mixture was cooled to 0 °C. NaH (60% in mineral oil, 310 mg, 7.8 mmol) was added in small portions over 30 min, followed by dropwise addition of methyl iodide (0.48 mL, 1.09 g, 7.70 mmol). The mixture was stirred for 18 h during which time the solution was allowed to warm to rt, and then EtOAc (100 mL) was added. The mixture was washed with water (3 × 30 mL) and bring (2 × 30 mL), dried over $MgSO_4$, filtered and concentrated. Dialkyne **12d** was purified from the mixture by chromatography on silica gel (90:10 hexane:EtOAc) as a pale yellow oil (890 mg, 2.93 mmol, 94.4%). $[\alpha]_D^{22}$ −235 (*c* 0.52 in $CHCl_3$); HRMS (ESI-TOF) *m/z*: [M + Na] + Calcd for $C_{22}H_{22}NaO_2$ 341.1512; Found 341.1515; δ_{max} 2961, 2820, 1489, 1334, 1100, 753, 700 cm^{-1}; δ_H (500 MHz, $CDCl_3$) 7.48–7.44 (4H, m, ArH), 7.30–7.26 (6H, m, ArH), 4.25–4.20 (2H, m, CH), 3.48 (6H, s, OCH_3); 2.10–1.95 (4H, m, CH_2CH_2); δ_C (126 MHz, $CDCl_3$) 131.8, 128.5, 128.3, 122.7, 87.7, 86.1, 71.3, 56.5, 31.4; *m/z* (ESI) 340.9 (M^+ + Na). $IR_{(neat)}$ 3080, 3057, 3033, 2984, 2962, 2929, 2900, 2821, 2225, 1598, 1573, 1489, 1463, 1443, 1335, 1255, 1213 cm^{-1}. δ_H (500 MHz, $CDCl_3$) 7.41–7.47 (4H, m, Ar*H*), 7.27–7.32 (6H, m, Ar*H*), 4.26 (2H, t, *J* = 6.0 Hz, C*H*OR), 3.48 (6H, s, O*CH*$_3$)1.99 – 2.10 (4H, m, CH_2). δ_C (125 MHz, $CDCl_3$) 131.8 (CH), 128.3 (CH), 128.2 (C), 122.7 (C), 87.7 (C), 86.1 (C), 71.2 (CH) 56.5 (CH_3) 31.4 (CH_2). *m/z* (ESI) $[M + Na]^+$ 340.9. HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{22}H_{22}O_2Na$ 341.1512; Found 341.1515.

4.1.8. Tricarbonyl-(4S,7S)-4,7-dimethoxy-1,3-diphenyl-4,5,6,7-tetrahydro-2H-inden-2-one ruthenium 13d

In an ACE pressure tube under a nitrogen atmosphere ((3*S*,6*S*)-3,6-dimethoxyocta-1,7-diyne-1,8-diyl)dibenzene **12d** (747 mg, 2.35 mmol) was dissolved in anhydrous acetonitrile (12 cm^3) and nitrogen was bubbled for 15 min. $Ru_3(CO)_{12}$ (500 mg, 0.78 mmol) was added, the pressure tube was sealed and the mixture was heated at 100 °C for 5 days. The mixture was cooled to room temperature and the pressure tube was carefully opened into the fumehood. Then the volatiles were removed and the product was purified by flash chromatography on silica gel (eluent: Hexane to Hexane/EtOAc = 7:3) to give tricarbonyl-(4*S*,7*S*)-4,7-dimethoxy-1,3-diphenyl-4,5,6,7-tetrahydro-2*H*-inden-2-one ruthenium **13d** (716 mg, 1.35 mmol, yield: 57.4%) as yellow solid. Crystals for X-ray crystallography were grown by slow diffusion of hexane into an acetone solution of the compound. m.p. 172.3 °C dec. $[\alpha]_D^{25}$ + 65 (*c* 0.10, $CHCl_3$). $IR_{(neat)}$ 3077, 3053, 2955, 2924, 2892, 2862, 2820, 2084, 2031, 2012, 1941, 1737, 1632, 1599, 1557, 1496, 1459, 1448, 1430, 1390, 1365, 1342, 1329, 1242, 1199 cm^{-1}. δ_H (500 MHz, $CDCl_3$) 7.75 (2H, d, *J* = 7.5 Hz, Ar*H*), 7.64 (2H, d, *J* = 7.3 Hz, Ar*H*), 7.33–7.41 (4H, m, Ar*H*), 7.27–7.33 (2H, m, Ar*H*), 4.25 (1H, br. s, C*H*OR), 3.77 (1H, br. s., C*H*OR), 3.27 (3H, s, CH_3), 3.11 (3H, s, CH_3), 1.88–2.06 (4H, m, CH_2). δ_C (125 MHz, $CDCl_3$) 194.0 (C), 174.1 (C), 132.0 (C), 131.3 (C), 131.1 (CH), 130.1 (CH), 128.19 (CH), 128.14 (CH), 127.5 (CH), 127.4 (CH), 105.9 (C), 102.6 (C), 81.5 (CH), 81.4 (CH), 71.0 (CH), 67.7 (CH), 57.3 (CH_3), 56.0 (CH_3), 20.6 (CH_2), 20.5 (CH_2). *m/z* (ESI) $[M + H]^+$ 532.9; $[M + Na]^+$ 555.0. HRMS (ESI-TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{26}H_{22}O_6{}^{102}RuNa$ 555.0359; Found 555.0348.

4.1.9. Asymmetric hydrogenation of acetophenone

The alcohol formed by reduction of acetophenone has been reported and our procedures and characterisation followed the protocols reported [5b]. A typical asymmetric hydrogenation procedure is as follows; acetophenone (200 mg, 1.67 mmol), catalyst (1 mol%), iPrOH (0.5 mL) and H_2O (0.2 mL) were added to a small test tube containing a stirrer bar. TMAO (1.25 mg, 0.017 mmol, 1 mol%) was added, then the test tube was sealed in a Parr hydrogenator and charged with hydrogen to 30 bar, venting once. The sealed vessel was heated to 80 °C and stirred for 18 h. At the end of this time, the reaction was allowed to cool to rt, the pressure was carefully released and the sample was worked up and analyzed by chiral GC [5b]. At the end of this time the reaction was allowed to cool to rt and EtOAc:hexane (1:4, ca. 10 mL) was added to dilute the sample. This solution was passed through celite and then silica gel to remove residues of catalyst. Removal of solvent gave the product which was analyzed by GC [5b]. The absolute configuration was assigned by comparison of GC spectroscopic data previously reported for this compound [5b].

Examples of conversion and enantiomeric excess determination for (*R*)-1-phenylethanol (spectra are in the Supporting Information); Table 3, Entry 9 (1 mol% OBn catalyst **13b**, 5% TMAO, 5% pyridine, IPA/ H_2O, 30 bar H_2, 80 °C, 18 h, > 99% conversion, 38.2% ee (*R*)) (CP-Chiralsil-Dex-Cβ 25 m × 0.25 mm × 0.25 μm, T = 110 °C, P = 18 psi, He gas) (*R)* isomer 11.62 min, (*S)* isomer 13.17 min. The ketone has a RT of 5.63 min.

Table 3, Entry 11 (1 mol% OBn catalyst **13b**, 10% TMAO, 10% pyridine, IPA/ H_2O, 30 bar H_2, 80 °C, 18 h, 66.0% conversion, 46% ee (*R*)) (CP-Chiralsil-Dex-Cβ 25 m × 0.25 mm × 0.25 μm, T = 110 °C, P = 18 psi, He gas) (*R)* isomer 11.88 min, (*S)* isomer 13.32 min. The ketone has a RT of 5.45 min.

5. Data sharing statement

The research data (and/or materials) supporting this publication can be accessed at http://wrap.warwick.ac.uk/.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

^{1}H and ^{13}C NMR spectra. X-ray data (CCDC 1923113-1923117), Examples of Chiral GC of reduction products. Supplementary data to this article can be found online at https://doi.org/10.1016/j.ica.2019.119043.

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