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Journal of Organometallic Chemistry 593–594 (2000) 299–306

Journal of Organometallic Chemistry

Enantioselective hydride transfer hydrogenation of ketones catalyzed by [(η^6-*p*-cymene)Ru(amino acidato)Cl] and [(η^6-*p*-cymene)Ru(amino acidato)]$_3$(BF_4)$_3$ complexes

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Received 10 June 1999; accepted 27 July 1999

Dedicated to Professor Fausto Calderazzo on the occasion of his 70th birthday.

Abstract

The new complexes ($R_{Ru}S_C$, $S_{Ru}S_C$)-[(η^6-*p*Cym)Ru(L-Aze)Cl] (**6a**, **b**), ($R_{Ru}S_C$, $S_{Ru}S_C$)-[(η^6-*p*Cym)Ru(L-Pip)Cl] (**7a**, **b**), ($R_{Ru}R_{Ru}R_{Ru}S_CS_CS_CS_NS_NS_N$, $S_{Ru}S_{Ru}S_{Ru}S_CS_CS_CS_NS_NS_N$)-[{($\eta^6$-*p*Cym)Ru(L-Aze)}$_3$]($BF_4$)$_3$ (**8a**, **b**) and ($R_{Ru}R_{Ru}R_{Ru}S_CS_CS_CS_NS_NS_N$, $S_{Ru}S_{Ru}S_{Ru}S_CS_CS_CS_NS_NS_N$)-[{($\eta^6$-*p*Cym)Ru(L-Pip)}$_3$]($BF_4$)$_3$ (**9a**, **b**) (L-Aze = L-2-azetidinecarboxylate, L-Pip = L-2-piperidinecarboxylate) were prepared, characterized and used, together with the known [{(η^6-*p*Cym)Ru(L-Pro)}$_3$](BF_4)$_3$, **5** and [{(η^6-*p*Cym)Ru(L-Ala)}$_3$](BF_4)$_3$, **10** (L-Pro = L-prolinate, L-Ala = L-alaninate), in hydride transfer reduction of acetophenone, a series of substituted acetophenones and several other ketones with moderate to high conversions and enantioselectivities up to 86% e.e. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Amino acids; Asymmetric catalysis; Hydrogenation; Ketones; Ruthenium

1. Introduction

Transition metal complexes having the (η-ring)M fragment show many interesting properties with regard to both their co-ordination and structural chemistry as well as to their catalytic properties [1–5]. Some of these compounds are soluble in water and display examples of aqueous organometallic chemistry [6–12]. For example, [Cp*Rh(H_2O)$_3$]$^{2+}$ (Cp* = η^5-pentamethylcyclopentadienyl) reacts with an array of potential ligands, such as nucleobases, nucleotides, amino acids etc. [12]. Following the preparation and characterization of monomeric [Cp*M(Aa)Cl] (M = Rh, Ir) and [(η^6-*p*Cym)Ru(Aa)Cl] (*p*Cym = 4-isopropyltoluene, *p*-cymene) complexes [8,9], we have recently shown that the cationic fragments [(η-ring)M(Aa)]$^+$ undergo facile trimerization upon Cl^- removal with Ag^+ to afford the complexes [{(η-ring)M(Aa)}$_3$](BF_4)$_3$ [13]. Based on NMR and X-ray diffraction data, it could be established, that in the observed trimers the three metal centers all had the same configuration, that is only two of the possible four diastereomers were formed. As an example, with an (*S*)-aminoacidate ligand only the $S_MS_MS_MS_CS_CS_C$ (σ) or the $R_MR_MR_MS_CS_CS_C$ (ρ) isomers were obtained indicating that trimerization took place with a high degree of self-recognition. However, in solution a fairly fast diastereomerization of the ρ and σ isomers were observed.

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0022-328X/00/$ - see front matter
PII: S0022-328X(99)00433-7

Enantioselective reduction of prochiral ketones is a synthetically most valuable reaction [14] and several catalysts and procedures have been developed such as catalytic hydrogenation [15–17], hydrogen transfer [1,18–21] or hydrosilylation, followed by cleavage of the resulting silyl ether [22]. Especially notable are the results of Noyori, Ikariya et al. who introduced the use of chiral diamines and their derivatives (e.g. tosyl amides) as chiral inductor ligands in various Ru-complexes [1,23,24]. This highly successful approach made possible the enantioselective hydrogenation and hydrogen transfer reduction of a wide array of prochiral ketones with yields and e.e.-s close to 100% in many cases under mild conditions. In particular, and relevant to this study, it was shown that [(η^6-*p*Cym)-Ru{(1*S*, 2*S*)-TsDPEN}Cl] (**1**; (1*S*, 2*S*)-TsDPEN = (1*S*, 2*S*)-*N*-(*p*-toluenesulfonyl)-1,2-diphenylethylenediamine) afforded a stable 16 e complex, [(η^6-*p*Cym)Ru{(1*S*, 2*S*)-TsDPENH$_{-1}$}] (**2**) upon H^+ abstraction from the primary amino nitrogen by base (KOH) and concomitant Cl^- loss; this further reacted smoothly with 2-propanol to yield an 18 e hydride, [(η^6-*p*Cym)RuH{(1*S*, 2*S*)-TsDPEN}] (**3**). All three complexes were fully characterized by single crystal X-ray diffraction. Hydride **3** is an active and highly enantioselective catalyst of hydrogen transfer from 2-propanol to various ketones without the need of additional base. Analogous isolobal Rh- and Ir-complexes with Cp* as spectator ligand have been prepared by Murata, Ikariya and Noyori [25] and by Mashima, Abe and Tani [26,27]; these showed comparable selectivity but somewhat less activity in the hydrogen transfer reduction of ketones as their Ru-based analogs.

Recently we have communicated part of our results on the catalytic activity of the trimeric [{(η-ring)M(Aa)}$_3$](BF$_4$)$_3$ and the monomeric [(η-ring)M-(Aa)Cl] complexes in carbonyl-selective reduction of unsaturated aldehydes and in the enantioselective reduction of prochiral ketones with H-transfer from 2-propanol [13]. Among the several Ru-, Rh- and Ir-containing catalysts, [(η^6-*p*Cym)Ru(L- or D-proline)Cl] (**4a**, **b**) and the corresponding trimers (**5a**, **b**) gave the best combination of rate and selectivity, exemplified by a turnover frequency of TOF = 146 h^{-1} and 71% e.e. in reduction of acetophenone in refluxing 2-propanol with **4**. Obviously, amino acids are attractive, cheap and available ligands in catalysts inducing chirality in reductions of prochiral substrates, such as ketones. Such an approach, aimed mainly at synthetic application has been recently described by Furukawa et al. [28]. Here we present our further studies undertaken to establish the scope of the reaction and get a deeper insight into the reaction mechanism. To this end, analogous compounds to the most successful [(η^6-*p*Cym)Ru(L- or D-proline)Cl] catalyst were prepared with L-2-azetidinecarboxylic acid [(*S*)-(−)-azetidinecarboxylic acid, L-Aze] and L-2-piperidinecarboxylic acid [(*S*)-(−)-2-piperidinecarboxylic acid, L-Pip] as ligands and their catalytic properties are discussed here, too. Some results of the catalytic studies were already disclosed as a poster presentation [29].

2. Results and discussion

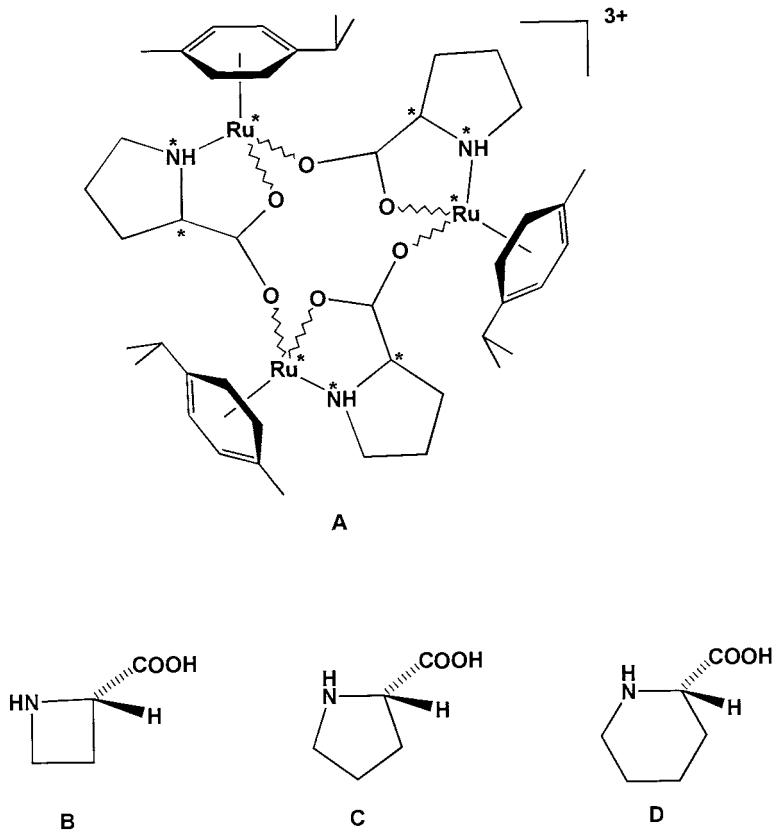
2.1. Preparation of ($R_{Ru}S_C$, $S_{Ru}S_C$)-[(η^6-*p*Cym)Ru-(L-Aze)Cl] (**6a**, **b**), ($R_{Ru}S_C$, $S_{Ru}S_C$)-[(η^6-*p*Cym)Ru-(L-Pip)Cl] (**7a**, **b**), ($R_{Ru}R_{Ru}R_{Ru}S_CS_CS_CS_NS_NS_N$, S_{Ru}-$S_{Ru}S_{Ru}S_CS_CS_CS_NS_NS_N$)-[{($\eta^6$-*p*Cym)Ru(L-Aze)}$_3$](BF$_4$)$_3$ (**8a**, **b**) and ($R_{Ru}R_{Ru}R_{Ru}S_CS_CS_CS_NS_NS_N$, $S_{Ru}S_{Ru}S_{Ru}S_C$-$S_CS_CS_NS_NS_N$)-[{(η^6-*p*Cym)Ru(L-Pip)}$_3$](BF$_4$)$_3$ (**9a**, **b**)

Since the best catalytic performance in our studies was observed [13,29] with catalyst **4a**, **b** containing proline as a ligand of a rigid carbon skeleton, we prepared the analogous compounds **6** and **7** with L-Aze and L-Pip similarly (the general formulae are shown on Scheme 1). The new complexes were synthesized according to the general route described in Ref. [13], by replacement of the acetylacetonato ligand in [(η^6-*p*Cym)Ru(acac)Cl]. Compounds **6** and **7** were obtained in the isomeric ratio **6a**:**6b** = 78:22 and **7a**:**7b** = 63:37.

Chloride is easily removed from these neutral chloro complexes with Ag^+ and the resulting cations undergo trimerization to afford mixture of only two diastereomers, in **8a**:**8b** = 75:25 and **9a**:**9b** = 90:10 ratios. According to these data, compounds **6**–**9** resemble the analogous Ru-complexes with various other amino acids in that their solids contain a mixture of the ρ and σ isomers, in contrast to the [(η^5-Cp*)Rh(Aa)] and [(η^5-Cp*)Ir(Aa)] derivatives [13], which in the solid form were exclusively obtained as a single diastereomer. Although it was not investigated in detail, diastereoisomerization of the trimers may also take place in solutions with polar solvents, similar to analogous [{(η^6-*p*Cym)Ru(Aa)}$_3$]$^{3+}$ complexes [13].

2.2. Protic equilibria in aqueous solution

In aqueous solutions [(η^6-*p*Cym)Ru(Aa)Cl] and [{(η^6-*p*Cym)Ru(Aa)}$_3$]$^{3+}$ complexes solvolyze to give the [(η^6-*p*Cym)Ru(Aa)(H$_2$O)]$^+$ aquo species. pH-static titrations, similar to those described in Ref. [30] indicated proton dissociation processes in basic solutions of these complexes. Using standard methods of coordination chemistry (see Section 4), we made pH-potentiometric titrations of [(η^6-*p*Cym)Ru(L-Pro)Cl], **4** and [{(η^6-*p*Cym)Ru(L-Ala)}$_3$](BF$_4$)$_3$, **10**. In the 3 < pH < 11 range the titration curves could be well fitted with the



Scheme 1. (A) Schematic representation of the cation of the trimer **5**. (B) L-2-Azetidine carboxylic acid. (C) L-Proline. (D) L-2 Piperidine carboxylic acid.

assumption of only one protonation/deprotonation process. The acidity constants were calculated as $pK_a = 8.62 \pm 0.06$ (**4**) and $pK_a = 8.49 \pm 0.04$ (**10**). By comparison to known π-arene-aqua complexes of ruthenium(II) [31], e.g. to $[(\eta^6\text{-}p\text{Cym})\text{Ru(bipy)}(H_2O)]^+$ having a $pK_a = 7.2 \pm 0.1$, this process can be ascribed to the deprotonation of coordinated water:

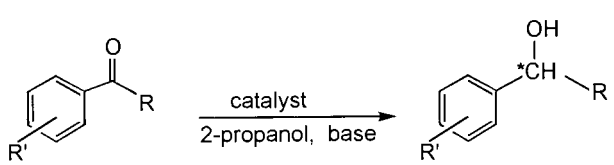
$$[(\eta^6 - p\text{Cym})\text{Ru(Aa)}(H_2O)]^+ \rightleftharpoons [(\eta^6 - p\text{Cym})\text{Ru(Aa)(OH)}] + H^+ \quad (1)$$

A very important conclusion from these measurements on proton dissociation is that in aqueous solutions, under ambient conditions show no sign of proton dissociation from the coordinated amine functionality, not even at fairly high pH. This is in contrast to what had been observed by Noyori et al. in non-aqueous solutions and what is regarded as a prerequisite of a high activity in hydrogen transfer from 2-propanol [24]. In fact, the solutions remained yellow throughout the titrations up to the upper limit of the investigated pH-range, while both the amine-deprotonated complex (**2**) and the hydride derived from it (**3**) are red, as well as the catalytically active solutions (in 2-propanol) of our complexes.

2.3. Catalytic activity

2.3.1. Hydrogen transfer from 2-propanol

Complexes of the general formula $[(\eta^6\text{-}p\text{Cym})\text{Ru(Aa)Cl}]$ or $[\{(\eta^6\text{-}p\text{Cym})\text{Ru(Aa)}\}_3](BF_4)_3$ are active catalysts for the reduction of ketones by hydride transfer from 2-propanol (Scheme 2), and in case of prochiral substrates the reaction takes place with high enantioselectivity. However, it deserves attention that the observed e.e.-s never exceeded 90%. After starting the reaction the enantioselectivity increased sharply with increasing conversion, then leveled off or decreased slightly with high conversions at high substrate/catalyst loadings [13]. Although the catalysts with open-chain aminoacidato ligands usually show high activity, the highest enantioselectivity was observed with complexes of L-proline, and this was attributed to its having a relatively bulky and rigid ring structure.



Scheme 2.

Table 1
Reduction of acetophenone by hydrogen transfer from 2-propanol catalyzed by **5**, **8**, **9** and **10** [a]

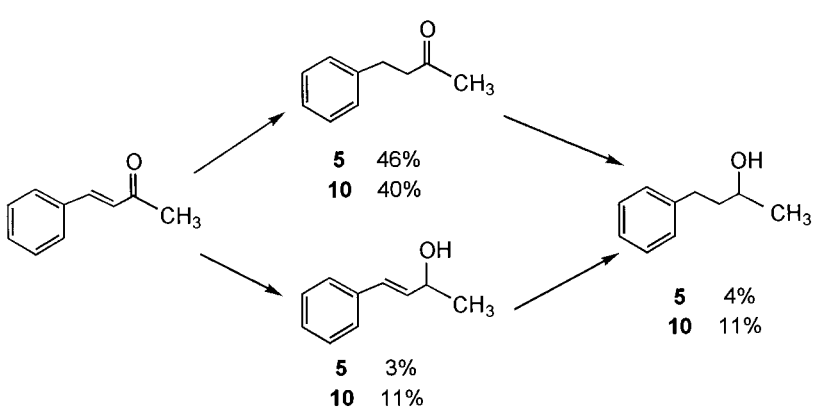
No.	Catalyst	t (h)	TON	e.e. (%) (configuration)	T (°C)	Remark ([catalyst]/[base]/[substrate])
1	**5**	48	6	78 (R)	21	A
2	**5**	1	20	80 (R)	50	A
3	**5**	1	97	75 (R)	83	A
4	**5**	1	48	74 (R)	83	(1/1/50)
5	**5**	1	168	69 (R)	83	(1/1/200)
6	**5**	1	380	67 (R)	83	(1/1/1000)
7	**5**	1	154	70 (R)	83	B
8	**5**	1	94	68 (R)	83	A, P
9	**8**	1	70	55 (R)	83	A
10	**8**	1.5	10	66 (R)	50	A
11	**9**	0.5	97	60 (S)	83	A
12	**9**	1	62	69 (S)	50	A
13	**9**	48	40	76 (S)	21	A
14	**10**	1	38	6 (R)	83	A
15	**10**	1	13	6 (R)	83	A, P
16	**10**	1	92	13 (R)	83	B

[a] For general conditions and for the pretreatment of the catalyst see Section 4. A, [catalyst]/[base]/[substrate] = 1/1/100; B, [catalyst]/[base]/[substrate] = 1/2/214, P, pretreatment of the catalyst; TON, mol reacted substrate/mol catalyst.

The same complexes proved to be almost completely inactive for the *hydrogenation* of ketones in aqueous/organic biphasic systems under mild conditions. Therefore we have undertaken a detailed study of some of the known (**5**, **10**) and the new (**8**, **9**) complexes with regard to the scope and mechanism of catalysis by these compounds. The basic findings are contained in Tables 1–3. Because of the varying [substrate]/[catalyst] ratios, the absolute turnover numbers (TON) and not the conversions (%) are used to characterize the extent of the reaction.

Reduction of acetophenone, several substituted acetophenones and other ketones can be accomplished with all the catalysts investigated, showing good rates and enantioselectivities up to 86% e.e. In general, trimers **8** and **9** show comparable reactivity to **5**, i.e. the ring size does not exert a dramatic influence on this catalytic property, although data of Tables 1–3 show a **8** < **5** < **9** order of reactivity towards the same substrate. Strikingly, this similarity does not hold for the enantioselectivity: **5** and **8** both catalyze the formation of alcohols with (*R*)-configuration, conversely, reactions with **9** as catalyst produce the (*S*)-alcohols. At the moment we do not have the clue to this intriguing observation. It is also noted, that while the catalytic activity of **9** is close to that of **5** with all substrates, its enantioselectivity is usually less, and in some cases even large differences can be observed (e.g. Table 3, no. 7 and 12). In comparison to **5**, **8** and **9**, complex **10,** having the more flexible alaninate ligand, proved to be a generally more active but much less enantioselective catalyst for ketone reduction.

The reaction is applicable to a large number of different ketonic substrates as shown by Tables 1–3. Acetophenone and its substituted derivatives usually show good reactivity, except 2-hydroxy-acetophenone which is totally unreactive. Interestingly, propiophenone is also slow to react, however its 3- and 4-chloro-derivatives can be easily reduced. Where applicable, comparison of the reactivities and the Hammett sub-



Scheme 3.

Table 2
Reduction of substituted acetophenones by hydrogen transfer from 2-propanol catalyzed by **5**, **8**, **9** and **10** [a]

No.	Substituent	Catalyst	TON	e.e. (%) (configuration)	Remark
1	4-Methyl-	**5**	77	61 (R)	A
2		**5**	104	60 (R)	B
3		**5**	42	62 (R)	A, P
4		**5**	15 [b,c]	66 (R)	A
5		**8**	75[b]	51 (R)	A
6		**9**	91	54 (S)	A
7		**9**	62 [b,c]	68 (S)	A
8		**10**	13	6 (R)	A, P
9		**10**	94	1 (R)	B
10	4-Methoxy-	**5**	64	45 (R)	B
11		**10**	84	13 (S)	B
12	4-Chloro-	**5**	95	55 (R)	A, P
13		**5**	93	56 (R)	A
14		**5**	118	54 (R)	B
15		**8**	99	44 (R)	A
16		**8**	13 [c,d]	50 (R)	A
17		**9**	99	44 (S)	A
18		**9**	62 [b,c]	68 (S)	A
19		**10**	5	2 (R)	A, P
20		**10**	55	1 (R)	B
21	4-Bromo-	**5**	141	50 (R)	B
22		**10**	139	8 (R)	B
23	2-Hydroxy-	**5**	0	–	B
24		**10**	0	–	B

[a] For general conditions and for the pretreatment of the catalyst see Section 4. A, [catalyst]/[base]/[substrate] = 1/1/100; B, [catalyst]/[base]/[substrate] = 1/2/214; P, pretreatment of the catalyst; TON, mol reacted substrate/mol catalyst.
[b] Reaction time, 1.5 h; temperature, 83°C.
[c] Reaction time, 1 h; temperature, 50°C.
[d] Reaction time, 2 h; temperature, 83°C.

stituent constants (σ) indicates a general trend of increasing rates with increasing σ (Table 2, no. 2, 9: -0.170; no. 10, 11: -0.268; no. 14, 20: 0.227, no. 21, 22: 0.232; Table 3, no. 3, 4: 0.227, no. 5, 6: 0.373), although no quantitative linear free energy relationship can be established based on this limited set of data. 3-Methyl-2-cyclohexene-1-one was reduced with an almost complete selectivity towards the C=O function and the product contained only a few percent of *cis*/*trans*-3-methylcyclohexanol (Table 3). On the other hand, benzalacetone reacted almost exclusively as an olefin (Scheme 3); accordingly, in separate experiments both methyl-benzyl-ketone and methyl-phenethyl-ketone showed only moderate/low reactivity (TON 12 and 26 (with **5**), 15 and 69 (with **10**), respectively).

Reaction *rates* increase sharply with the temperature in case of all catalysts. As an example, in the hydrogenation of acetophenone with **5**, only six turnovers could be realized in 48 h at 21°C (turnover frequency, TOF = 0.125 h^{-1}), while the TON rose to 97 in 1 h (= TOF) at 83°C (see also Table 1, no. 11–13). The reaction rate is also a function of the substrate concentration and seems to level off at high [substrate]/[catalyst] ratios (see e.g. Table 1, no. 3–6). On the other hand, the *enantioselectivity* of a given catalyst is only slightly dependent on the same parameters. It is generally observed, that the slower reactions at lower temperatures result in a higher optical yield, and the faster reactions at higher substrate concentrations are somewhat less selective. However, both effects are manifested only in a range of a few percent e.e. (e.g. Table 1, no. 4–6, Table 2 no. 1, 4, 15, 16). It seems, that the enantioselectivity provided by catalyst **9** is somewhat more sensitive to the temperature that with **5**, **8** and **10** (see e.g. Table 1, no. 11–13, Table 2, no. 6–7, no. 17–18).

In related systems, Lemaire et al. [32,33] and de Bellefon et al. [34] studied the transfer hydrogenation of acetophenone catalyzed by π-arene–Rh complexes with chiral chelating diamine ligands using 2-propanol as H-donor. It is suggested that at high substrate concentrations the primary product of the catalytic cycle, (*R*)-1-phenylethanol, while still coordinated to Rh, serves as an H-donor for reduction of another molecule of acetophenone. This could account for the lower e.e.-s at high substrate concentrations and for the increase of e.e. with increasing conversion [32] —

Table 3
Reduction of various ketones by hydrogen transfer from 2-propanol catalyzed by **5**, **8**, **9** and **10** [a]

No.	Substrate	Catalyst	t (h)	TON	e.e. (%) (configuration)	Remark ([catalyst]/[base]/[substrate])
1	Propiophenone	**5**	1	4	n.d.	B
2		**10**	1	6	n.d.	B
3	4-Chloro-propiophenone	**5**	1	103	54 (R)	B
4		**10**	1	145	7 (R)	B
5	3-Chloro-propiophenone	**5**	1	135	52 (R)	B
6		**10**	1	195	5 (R)	B
7	1-Indanone	**5**	2	60	74 (R)	A
8		**5**	2	8	86 (R)	A, P
9		**5**	1	24	84 (R)	(1/1/50)
10		**8**	2	30	74 (R)	A
11		**9**	2	35	24 (S)	(1/1/50)
12		**9**	2	31	16 (S)	A
13	3-Methyl-2-cyclohexene-1-one [b]	**5**	2	17	65 (R)	A
14		**5**	24	29	63 (R)	A
15		**8**	2	10	51 (R)	A
16		**9**	2	23	50 (S)	A

[a] For general conditions and for the pretreatment of the catalyst see Section 4. All reactions at 83°C. A, [catalyst]/[base]/[substrate] = 1/1/100; B, [catalyst]/[base]/[substrate] = 1/2/214; P, pretreatment of the catalyst; TON, mol reacted substrate/mol catalyst; n.d., not determined.
[b] Reactions 13–16: conversions shown for the major product, 3-methyl-2-cyclohexene-1-ol. Minor product: *cis*/*trans*-3-methyl-cyclohexanol ($\leq 1\%$).

same features as found with our catalysts [13]. An important assumption here is in that 1-phenylethanol can be enantioselectively dehydrogenated by the same catalyst in the presence of a suitable hydrogen acceptor (kinetic resolution). In fact, under conditions comparable to those of ketone reductions, with **5** as catalyst and acetone as the hydrogen acceptor we observed a slow dehydrogenation (TON = 9 in 3.3 h) of racemic 1-phenylethanol, however, with no sign of kinetic resolution.

2.3.2. Hydrogenation experiments

Complexes **4**, **5** and **10** showed low activity in hydrogenation of acetophenone or substituted acetophenones in organic solvents or in aqueous/organic biphasic systems. The best result [22% conversion to (*R*)-1-phenylethanol, e.e. 8%] was achieved in hydrogenation of acetophenone with **10** in methanolic solution (0.43 mmol substrate, 0.01 mmol catalyst, 0.02 mmol base, 2 ml MeOH, 15 bar H_2, room temperature, 20 h). Aqueous solutions of **4** and **10** under H_2 pressure at catalytic conditions did not show the characteristic color change to red, displayed by active catalyst solutions in 2-propanol. Accordingly, no or negligible conversions of acetophenone or water soluble olefins (maleic, fumaric and itaconic acid) were detected in aqueous systems under various reaction conditions (up to 15 bar H_2, $3 < pH < 9$, 20–60°C). Interestingly, there was a slow hydrogenation of $[HCO_3]^-$ to $[HCO_2]^-$ in 0.2 M $NaHCO_3$ solution (2 mM **10**, 10 bar H_2, 55°C; HPLC detection, TOF = 0.1 h^{-1}).

3. Conclusions

The title complexes with chiral aminoacidate ligands, such as prolinate, azetidine carboxylate, piperidine carboxylate and alaninate are useful catalysts for the enantioselective reduction of prochiral ketones by hydride transfer from 2-propanol. However, the same complexes show poor hydrogenation activity for reduction of ketones and olefinic substrates in *aqueous* solution. The catalytically active species in ketone reductions in 2-propanol may be similar to the hydride **3**, characterized by Noyori et al. [24], the formation of which requires deprotonation of a coordinated amine group of the ligand. However, according to the results of our pH-metric measurements on **4** and **10** (together with the lack of characteristic spectral changes), in the potentiometrically accessible pH range (≤ 11) in aqueous solutions there is no such deprotonation in the [(η^6-*p*Cym)Ru(Aa)Cl] complexes or in the corresponding trimeric or solvolyzed derivatives. This may well account for the observed lack of catalytic activity in aqueous solutions.

4. Experimental

4.1. General

Infrared spectra were recorded on Perkin-Elmer 783, Paragon 1000PC and 1330 spectrophotometers (range 4000–200 cm^{-1}) using Nujol mulls between polyethylene sheets or dichloromethane solutions between NaCl plates. Carbon, hydrogen, and nitrogen

analyses were performed using a Perkin-Elmer 240B microanalyzer. NMR data were recorded on a Varian UNITY 300 spectrometer operating at 299.95 (^{1}H) and 75.4 (^{13}C) MHz and on a Bruker AM360 instrument. Chemical shifts are expressed in ppm upfield from $SiMe_4$. Coupling constants J are given in hertz. CD spectra were determined in 0.1 or 1 cm path length cell by using a Jasco-710 apparatus, at concentrations ca. 5×10^{-4} M. Gas chromatographic measurements were made on a Hewlett Packard 5890A equipment. The amino acids, acetophenone, substituted acetophenones and citral were purchased from Aldrich, cinnamaldehyde from Schuchardt and were used as received. Reagent grade 2-propanol was purified with standard methods. Other chemicals were highest grade commercial products of Aldrich.

4.2. Preparation of the chloride compounds [(η^6-pCym)Ru(Aa)Cl] (**6**, **7**)

To a solution of the acetylacetonate compound [(η^6-*p*Cym)Ru(acac)Cl] (acac = acetylacetonate) (1.0 mmol) in methanol (20 cm^3) the appropriate amino acid (Aa) (1.0 mmol) was added. The resulting solution was stirred for 24 h and then filtered through Kieselguhr to eliminate any solid residue. The solvent was then removed in vacuum to leave a solid residue. Then it was redissolved in a minimum amount of methanol and the orange products were precipitated by addition of diethylether. The solids were filtered off, washed with diethylether and vacuum dried. They crystallize with one molecule of water.

Complex **6**: Yield 80%, (**6a**:**6b** molar ratio, 78:22). Anal. Found: C, 44.0; H, 5.3; N, 4.0%. Anal. Calc.: C, 43.3; H, 5.7; N, 3.6%. $C_{14}H_{22}NClO_3Ru$. IR (Nujol): ν(CO) 1620(vs); ν(NH) 3200(m); 3510(m) cm^{-1}. CD spectrum (5×10^{-4} mol l^{-1}, methanol) $[\theta]_l$ values of maxima, minima and nodes (λ, nm); +0.15 (410), 0 (390), −0.3 (360), −0.25(340), −0.35 (320), −0.5 (290), −1 (230). ^{1}H-NMR (CD_3OD, 20°C): **6a** δ 1.25 (3H, d, ^3J(HH) = 6.9, Me (*i*-Pr)), 1.26 (3H, d, ^3J(HH) = 6.8, Me (*i*-Pr)), 2.21 (3H, s, Me), 2.2–2.3 (2H, m, CH_2), 2.8 (1H, m, CH (*i*-Pr)), 2.8, 3.92 (2H, 2 × m, CH_2N), 4.08 (1H, m, C*H), 4.37 (1H, m, NH), 5.44, 5.66 (2H, AB system, $J(H_AH_B)$ = 5.9), 5.51, 5.61 (2H, AB system, $J(H_AH_B)$ = 5.6); **6b** δ 1.18, 1.20 (6H, 2 × d, ^3J(HH) = 7.1, 2Me (*i*-Pr)), 2.11 (3H, s, Me).

Complex **7**: Yield 94%, (**7a**:**7b** molar ratio, 63:37). Anal. Found: C, 45.7; H, 6.2; N, 3.3%. Anal. Calc.: C, 46.1; H, 6.2; N, 3.4%. $C_{16}H_{26}NClO_3Ru$. IR(Nujol): ν(CO) 1600(vs); ν(NH) 3160(m); 3520(m) cm^{-1}. CD spectrum (5×10^{-4} mol l^{-1}, methanol) $[\theta]_l$ values of maxima, minima and nodes (λ, nm); +0.3 (410), 0 (380), −0.3 (360), 0 (330), +0.1 (310), 0 (290), −0.4 (230). ^{1}H-NMR (CD_3OD, 20°C): **7a** δ 1.29, 1.30 (6H, 2 × d, ^3J(HH) = 6.8, 2Me (*i*-Pr)), 2.13 (3H, s, Me), 3.5 (1H, sp, CH (*i*-Pr)), 3.5 (1H, m, C*H), 5.42, 5.5 (2H, AB system, $J(H_AH_B)$ = 6.1), 5.5, 5.62 (2H, AB system, $J(H_AH_B)$ = 5.9); **7b** δ 1.28, 1.30 (6H, 2 × d, 2Me (*i*-Pr)), 2.10 (3H, s, Me), 5.5, 5.69 (2H, AB system), 5.5, 5.70 (2H, AB system).

4.3. Preparation of the complexes [{(η^6-pCym)Ru-(Aa)}$_3$](BF$_4$)$_3$ (**8**, **9**)

An equimolar amount of $AgBF_4$ was added to a 0.05 M solution of the corresponding [(η^6-*p*Cym)Ru(Aa)Cl] compound in methanol (20 cm^3). The mixture was stirred for 1 h in the absence of light and the precipitated AgCl was filtered off. The resulting solution was concentrated at reduced pressure to about 2 cm^3. Addition of diethylether completed the precipitation of yellow solids which were filtered off, washed with diethylether, and vacuum dried. The compounds crystallize with three water molecules.

Complex **8**: Yield 70%, (**8a**:**8b** molar ratio, 75:25). Anal. Found: C, 38.6; H, 4.7; N, 3.4%. Anal. Calc.: C, 38.2; H, 5.0; N, 3.2%. $C_{42}H_{66}N_3B_3F_{12}O_9Ru_3$. IR(Nujol): ν(CO) 1580(vs); ν(NH) 3280(m); ν(OH) 3620(m) cm^{-1}. CD spectrum (5×10^{-4} mol l^{-1}, acetone) $[\theta]_l$ values of maxima, minima and nodes (λ, nm); +30000 (410), 0 (340), −5000 (325), 0 (315), +1000 (310), 0 (300), −2000 (280), 0 (260) ^{1}H-NMR ($CD_3)_2CO$, 20°C): **8a** δ 1.38 (3H, d, ^3J(HH) = 6.8, Me (*i*-Pr)), 1.39 (3H, d, ^3J(HH) = 7.1, Me (*i*-Pr)), 2.50 (3H, s, Me), 2.4, 2.84 (2H, m, CH_2), 2.91 (1H, sp, CH (*i*-Pr)), 3.88 (1H, m, C*H), 4.39, 4.58 (2H, m, CH_2N), 5.89 (1H, m, NH), 5.89, 6.18 (2H, AB system, $J(H_AH_B)$ = 6.0), 6.08, 6.16 (2H, AB system, $J(H_AH_B)$ = 6.0); **8b** δ 1.31, 1.33 (6H, 2 × d, 2 Me (*i*-Pr)), 1.20 (3H, d, Me(*i*-Pr), 7.6 (1H, m, NH).

Complex **9**: Yield 91%, (**9a**:**9b** molar ratio, 90:10). Anal. Found: C, 41.3; H, 5.1; N, 3.2%. Anal. Calc.: C, 41.1; H, 5.6; N, 3.0%. $C_{48}H_{78}N_3B_3F_{12}O_9Ru_3$. IR (Nujol): ν(CO) 1580(vs); ν(NH) 3210(m); ν(OH) 3620(m) cm^{-1}. CD spectrum (5×10^{-4} mol l^{-1}, methanol) $[\theta]_l$ values of maxima, minima and nodes (λ, nm); 36500 (410), 0 (320), −2000 (305), 0 (0), −100 (280), 0 (270), +4000(240). ^{1}H-NMR ($CD_3)_2CO$, 20°C): **9a** δ 1.28 (3H, d, ^3J(HH) = 6.9, Me (*i*-Pr)), 1.30 (3H, d, ^3J(HH) = 6.8, Me (*i*-Pr)), 1.6–2.0 (5H, m, CH_2), 2.40 (1H, m, CH_2N), 2.45 (3H, s, Me), 2.8 (2H, m, CH(*i*-Pr), CH_2N), 3.95 (1H, d, ^3J(HH) = 11.6), C*H), 5.86, 6.02 (2H, AB system, $J(H_AH_B)$ = 5.4), 6.0, 6.32 (2H, AB system, $J(H_AH_B)$ = 6.0); **9b** δ 2.5 (3H, s, Me), 4.2 (1H, d, C*H).

4.4. Transfer hydrogenation experiments, standard reaction conditions

Catalyst (0.01 mmol), HCOONa (0.02 mmol); as 100 μl 0.2 M aqueous solution, 2-propanol (10 ml), ace-

tophenone (0.21 ml, 2.00 mmol), reflux (83°C), nitrogen atmosphere. The components of the reaction mixture, except acetophenone, were mixed under nitrogen at room temperature in a flask which was then equipped with a reflux condenser and immersed to an oil bath of 83°C. Pretreatment of the catalysts was achieved by refluxing this solution for the specified time (usually 1 h). To the boiling solution the acetophenone (0.21 ml) was added in 1 ml of 2-propanol. The reactions were monitored by gas–liquid chromatography using a Cyclodextrin column (CP-Cyclodex-B 236M, 25 m × 0.25 mm × 0.25 μm film, 110°C).

4.5. pH-potentiometric titrations

Proton dissociation constants were determined by titrating the solution of the complexes (5–13 mM) with carbonate-free potassium hydroxide (0.2 M) in the pH range of 3–11. Argon was passed through the stirred solutions to keep out oxygen and carbon dioxide. Measurements were made at 25°C using a Radiometer ABU 91 autoburette equipped with a Radelkis OP0808P combined glass electrode calibrated against 0.05 M potassium hydrogen phtalate. The acid dissociation constants were calculated by means of the general computational program PSEQUAD [35].

Acknowledgements

We thank the financial support provided by the Dirección General de Investigación Cientifica y Técnica, Spain (Grant PB96/0845) and the National Scientific Research Foundation (OTKA) of Hungary (Grant T029934). F. Joó is grateful to Iberdrola S.A. for a visiting professorship at the University of Zaragoza in 1995/1996 during which this research was initiated. The valuable experimental contribution of Ms Mária Sági and the skilful technical assistance of Ms Ildikó Varga are gratefully acknowledged.

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