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Studies on the rhodium- and ruthenium-catalyzed asymmetric hydrogenation of α-dehydroamino acids using a family of chiral dipyridylphosphine ligand (P-Phos)

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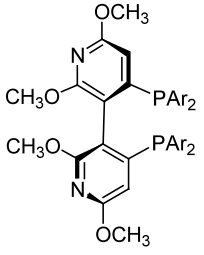
Abstract—The applications of the chiral dipyridylphosphine ligand P-Phos and its derivatives Tol-P-Phos and Xyl-P-Phos in Ru- and Rh-catalyzed hydrogenations of the methyl esters of a variety of (*Z*)-2-acetamido-3-arylacrylic acids have been studied systematically. The results show that the electronic and steric properties of these ligands have significant influences on the enantioselectivity of the reduction. Rh and Ru complexes of the same dipyridylphosphine ligand family exhibit different trends in enantioselectivity toward the same substrate.

1. Introduction

Asymmetric catalytic hydrogenation reactions have been recognized as one of the most powerful tools for obtaining a wide range of enantiomerically pure substances. Chiral amino acids are attractive targets for enantioselective synthesis on account of their vital role in the pharmaceutical industry both as nutritional supplements and as synthetic intermediates. Asymmetric catalytic hydrogenation of prochiral amidoacrylic acids represents a convenient method for the synthesis of such compounds. Rhodium catalysts containing chiral phosphine ligands have been proved the most successful catalysts for this type of reaction.[1] However, despite the fact that rhodium catalyzed asymmetric hydrogenation is a remarkably specific method for the production of chiral amino acids and certain closely related compounds, it is a reaction of limited scope.[2] Unlike the Rh-catalyzed hydrogenation of acetamidoacrylic acids and esters, the corresponding Ru chemistry has not been studied extensively[3,4] despite the wide application of ruthenium catalysts in the asymmetric hydrogenation if other types of substrates.

We have recently developed a highly effective dipyridylphosphine ligand P-Phos (**1**, P-Phos = 2,2′,6,6′-tetramethoxy-4,4′-bis(diphenylphosphino)-3,3′-bipyridine)[5] (Scheme 1) and a series of its derivatives Tol-P-Phos (**2**, Tol-P-Phos = 2,2′,6,6′-tetramethoxy-4,4′-bis-[di(*p*-tolyl) phosphino]-3,3′-bipyridine)[6] and Xyl-P-Phos (**3**, Xyl-P-Phos = 2,2′,6,6′-tetramethoxy-4,4′-bis[di(3,5-dimethylphenyl)phosphino]-3,3′-bipyridine)[7] for applications in the stereoselective Ru-catalyzed hydrogenation of 2-(6′-methoxy-2′-naphthyl)propenoic acid,[5] β-ketoesters[5–7] and aromatic ketones.[8] The Ru-P-Phos catalysts were found to be air-stable even in solution, indicating their potential for practical applications.[4,5] Herein, we present the results of our systematic investigations on the performance of the ligands **1**–**3** in the Ru- and Rh-catalyzed asymmetric hydrogenation of acetamidoacrylic acids and esters



(*R*)-**1**, Ar = C_6H_5, (*R*)-P-Phos
(*R*)-**2**, Ar = 4-$CH_3C_6H_4$, (*R*)-Tol-P-Phos
(*R*)-**3**, Ar = 3,5-$(CH_3)_2C_6H_3$, (*R*)-Xyl-P-Phos

Scheme 1.

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2. Results and discussion

2.1. Synthesis of ruthenium and rhodium complexes of (*R*)-P-Phos 1, (*R*)-Tol-P-Phos 2 and (*R*)-Xyl-P-Phos 3

Ruthenium complexes, $RuL^*(C_6H_6)Cl_2$ [L* = (*R*)-P-Phos (**Cat. 1a**), (*R*)-Tol-P-Phos (**Cat. 1b**),[6] (*R*)-Xyl-P-Phos (**Cat. 1c**)[7]] were prepared by mixing $[RuCl_2(C_6H_6)]_2$ with the corresponding dipyridylphosphine ligands in an 8:1 mixture of ethanol–benzene at 50–60°C for 1 h according to the method of Mashima et al.[9] The structures of these complexes were characterized by ^1H and ^{31}P NMR. The rhodium complexes, $RhL^*(COD)BF_4$ [L* = (*R*)-P-Phos (**Cat. 2a**), (*R*)-Tol-P-Phos (**Cat. 2b**), (*R*)-Xyl-P-Phos (**Cat. 2c**)] were prepared in situ by mixing $Rh(COD)_2BF_4$ with 1.05 equivalents of the corresponding dipyridylphosphine ligand in methanol under nitrogen and were characterized by ^{31}P NMR.

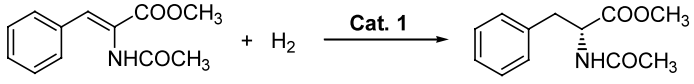
2.2. Asymmetric hydrogenation of methyl-(*Z*)-2-acetamidocinnamate using cationic Ru-complexes (Cat. 1a–Cat. 1c) as catalysts

In the initial study, (*Z*)-acetamidocinnamic acid methyl ester was chosen to be a model substrate. The $RuL^*(C_6H_6)Cl_2$ complex was found to be an effective catalyst for the asymmetric hydrogenation of (*Z*)-acetamidocinnamic acid methyl ester (Table 1). **Cat. 1c** showed almost no catalytic activity in aprotic solvents such as acetone, CH_2Cl_2 or THF (entries 1–3) while protic solvents such as methanol appear to be the solvent of choice (entry 4). Lowering of the reaction temperature from room temperature to 0°C did not enhance the enantioselectivity but resulted in the decrease of reaction rate (entry 10 versus entry 9). At high initial hydrogen pressures (entries 5–8), lower enantioselectivities were observed.

Having established the preferred conditions, the effectiveness of the catalysts **Cat. 1a**–**Cat. 1c** in the asymmetric hydrogenation of methyl (*Z*)-2-acetamidocinnamate and the free acid was evaluated (Table 2). P-Phos **1** showed better enantioselectivity over Tol-P-Phos **2** and Xyl-P-Phos **3** in this catalytic system. For example, the reaction was completed in 3 h affording a product with 90% ee when Ru-P-Phos complex **Cat. 1a** was employed (entry 2, Table 2), whereas the catalytic activity and enantioselectivity were substantially lower (64% conv., 73% ee) in the case of Ru-Xyl-P-Phos (**Cat. 1c**, entry 4, Table 2).

Further studies on the hydrogenation of a variety of other acetoamidoacrylic esters confirmed the consistently better enantioselectivity of **Cat. 1a**. In all cases, the desired products were found to have ee values of over 90% for **Cat. 1a**, with the best result being 97% ee (entry 1, Table 3). The details are summarized in Table 3. In general, for **Cat. 1a**–**c**, the substrate with an electron-withdrawing *ortho*-Cl-substitution on the phenyl ring reacted favorably to give product with higher enantiopurity when compared with substrates bearing *para*- or *meta*-Cl-substituents (entries 1–3 versus 4–9). On the other hand, electron-donating *para*-substituents led to lower levels of enantioselection (entries 10–15). More specifically, the replacement of a σ-electron-releasing methyl group with a π-electron-releasing methoxy group at the *para*-position did not show any significant changes on the eventual enantiomeric excess of the product.

Table 1. The effect of hydrogen pressure and substrate concentration on the hydrogenation of methyl (*Z*)-2-acetamidocinnamate catalyzed by **Cat. 1b**[a]



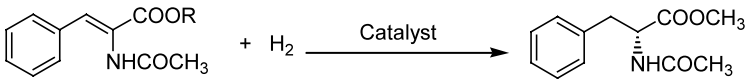
Entry	Catalyst	Solvent	Temp. (°C)	P_{H_2} (atm)	Time (h)	Conv. (%)[b]	Ee (%)[b]
1	**Cat. 1c**	Acetone	rt	4	12	<1	–[c]
2	**Cat. 1c**	CH_2Cl_2	rt	4	12	<1	–
3	**Cat. 1c**	THF	rt	4	12	<2	–
4	**Cat. 1c**	Methanol	rt	4	12	>99.9	77
5	**Cat. 1b**	Methanol	rt	1	3	>99.9	85
6	**Cat. 1b**	Methanol	rt	4	3	>99.9	83
7	**Cat. 1b**	Methanol	rt	15	3	>99.9	78
8	**Cat. 1b**	Methanol	rt	35	3	>99.9	77
9	**Cat. 1a**	Methanol	rt	1	3	>99.9	90
10	**Cat. 1a**	Methanol	0	1	18	53	89

[a] *Reaction conditions*: substrate (4 mg); substrate/catalyst = 100 (M/M); substrate concentration = 0.05–0.09 M.

[b] The conversion and ee values were determined by chiral GC with a 25 m×0.25 mm Chrompack Chirasil-L-Val column. *R* configuration was obtained for all products. The absolute configuration was determined by comparing the retention time with that reported in the literature (Ref. 10).

[c] The ee value could not be determined accurately due to the low conversion.

Table 2. Ruthenium-catalyzed asymmetric hydrogenation of (*Z*)-2-acetamidocinnamic acid and its methyl ester using **Cat. 1a–Cat. 1c**[a]



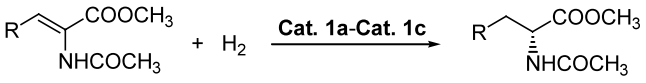
Entry	Substrate, R =	Catalyst	Time (h)	Conv.(%)[b]	Ee (%)[b]	Config.[c]
1	CH_3	**Cat. 1a**	2	96	88	*R*
2	CH_3	**Cat. 1a**	3	>99.9	90	*R*
3	CH_3	**Cat. 1b**	3	>99.9	85	*R*
4	CH_3	**Cat. 1c**	4	64	73	*R*
5	H	**Cat. 1a**	10	>99.9	90	*R*
6	H	**Cat. 1b**	10	>99.9	87	*R*
7	H	**Cat. 1c**	10	>99.9	85	*R*

[a] *Reaction conditions*: H_2 (1 atm); ambient temperature; substrate (4 mg); substrate concentration = 0.05–0.09 M in MeOH; substrate/catalyst = 100 (M/M).

[b] Conversion and ee values were determined by chiral GC with a 25 m×0.25 mm Chrompack Chirasil-L-Val column. The acids were converted to the corresponding methyl esters with methyl iodide/$KHCO_3$ before GC analysis.

[c] The absolute configuration was determined by comparing the retention time with that reported in the literature (Ref. 10).

Table 3. Ruthenium-catalyzed asymmetric hydrogenation of the derivatives of methyl (*Z*)-2-acetamidocinnamate using **Cat. 1a–Cat. 1c**[a]



Entry	Substrate, R =	Catalyst	Time (h)	Ee (%)[b]
1	2-Cl-C_6H_4	**Cat. 1a**	4	97
2	2-Cl-C_6H_4	**Cat. 1b**	4	95
3	2-Cl-C_6H_4	**Cat. 1c**	4	92
4	3-Cl-C_6H_4	**Cat. 1a**	4	91
5	3-Cl-C_6H_4	**Cat. 1b**	4	86
6	3-Cl-C_6H_4	**Cat. 1c**	4	82
7	4-Cl-C_6H_4	**Cat. 1a**	4	94
8	4-Cl-C_6H_4	**Cat. 1b**	4	84
9	4-Cl-C_6H_4	**Cat. 1c**	4	81
10	4-CH_3-C_6H_4	**Cat. 1a**	5	91
11	4-CH_3-C_6H_4	**Cat. 1b**	4	83
12	4-CH_3-C_6H_4	**Cat. 1c**	4	74
13	4-CH_3O-C_6H_4	**Cat. 1a**	5	90
14	4-CH_3O-C_6H_4	**Cat. 1b**	10	81
15	4-CH_3O-C_6H_4	**Cat. 1c**	10	76

[a] *Reaction conditions*: H_2 (1 atm); ambient temperature; substrate (4 mg); substrate concentration = 0.05–0.09 M in MeOH; substrate/catalyst = 100 (M/M); >99% conversion was observed in all cases.

[b] The conversion and ee values were determined by chiral GC with a 25 m×0.25 mm Chrompack Chirasil-L-Val column. *R* configuration was obtained for all products. The absolute configuration was determined by comparing the retention time with that reported in the literature (Ref. 10).

2.3. Asymmetric hydrogenation of methyl-(*Z*)-2-acetamidocinnamate using cationic Rh-complexes (Cat. 2a–Cat. 2c) as catalysts

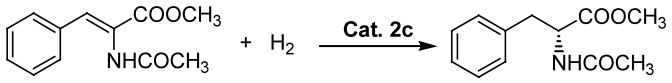
For broader investigations, it was of interest to compare the effects of the more conventional Rh complexes versus Ru-complexes in the same hydrogenation reactions (Table 4). Unlike the Ru-catalyzed asymmetric hydrogenation of methyl (*Z*)-2-acetamidocinnamate, Rh-catalyzed (**Cat. 2c**) asymmetric hydrogenation could be carried out in a variety of common organic solvents (entries 1–5, Table 4) although MeOH was again found to be the best solvent.

Thus, the reaction proceeded smoothly in methanol at ambient temperature with 1 atm of initial hydrogen pressure for 2 h to give a quantitative yield of the product with 90% ee (entry 5, Table 4). This result is in sharp contrast with the Ru case where the conversion and the product enantiopurity were only 64 and 73%, respectively, using the same ligand (i.e. **3**) under similar reaction conditions (entry 4, Table 2). Hydrogen pressure and temperature effects were also studied. Higher H_2 pressure led to a slight decrease in the enantiomeric purity of the product (entry 5 versus entries 7 and 8) whilst lower reaction temperature (0°C) facilitated an enhancement in the enantioselectivity but at the expense of reaction rate (entry 6).

(*Z*)-2-Acetamidocinnamic acid and a number of its derivatives were also hydrogenated with **Cat. 2a–Cat. 2c**. When (*R*)-P-Phos **1** or (*R*)-Tol-P-Phos **2** was used as ligand, the enantioselectivity of the Rh-catalyzed hydrogenation of methyl (*Z*)-2-acetamidocinnamate decreased dramatically in comparison with that observed when using (*R*)-Xyl-P-Phos **3** as a ligand (entries 2 and 3 versus entry 1, Table 5). Apparently, steric hindrance effects of the ligand enhanced the enantioselectivity. This trend was consistently observed in the hydrogenation of (*Z*)-2-acetamidocinnamic acid (entries 4–6). These results are completely opposite to the corresponding Ru-catalyzed hydrogenations. **Cat. 2c** was also effective for hydrogenating a variety of methyl (*Z*)-2-acetamidocinnamate derivatives leading to good enantioselectivities (92–94% ee, entries 7–11).

It has been reported that the hydrogenation of the enamide **4** catalyzed by (*R*)-BINAP-Ru(II) complexes

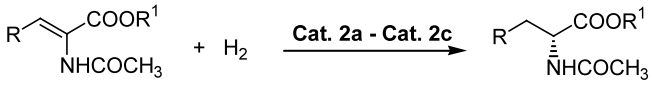
Table 4. The effect of solvent and hydrogen pressure on the Rh-catalyzed hydrogenation of methyl (*Z*)-2-acetamidocinnamate catalyzed with **Cat. 2c**[a]



Entry	Temp. (°C)	P_{H_2} (atm)	Solvent	Time (h)	Ee (%)[b]	Config.[c]
1	rt	1	Acetone	2	88	*R*
2	rt	1	CH_2Cl_2	2	87	*R*
3	rt	1	Toluene	2	86	*R*
4	rt	1	THF	2	87	*R*
5	rt	1	MeOH	2	90	*R*
6	0	1	MeOH	18	93	*R*
7	rt	35	MeOH	2	85	*R*
8	rt	15	MeOH	2	88	

[a] *Reaction conditions*: ambient temperature; 4 h; substrate (4 mg); substrate concentration = 0.09 M; substrate/catalyst = 100 (M/M); >99% conversion was observed in all cases.
[b] The conversion yield and ee value were determined by chiral GC with a 25 m×0.25 mm Chrompack Chirasil-L-Val column.
[c] The absolute configuration was determined by comparing the retention time with that reported in the literature (Ref. 10).

Table 5. Rhodium-catalyzed asymmetric hydrogenation of the derivatives of methyl (*Z*)-2-acetamidocinnamate using **Cat. 2a**–**Cat. 2c**[a]



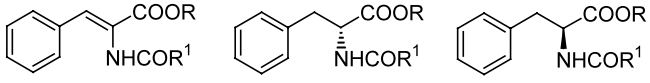
Entry	R =	R^1 =	Temp. (°C)	Catalyst	Time (h)	Conv. (%)[b]	Ee (%)[b]
1	C_6H_5-	CH_3	rt	**Cat. 2a**	2	>99.9	38
2	C_6H_5-	CH_3	rt	**Cat. 2b**	2	70	46
3	C_6H_5-	CH_3	rt	**Cat. 2c**	2	>99.9	90
4	C_6H_5-	H	rt	**Cat. 2a**	10	>99.9	64
5	C_6H_5-	H	rt	**Cat. 2b**	10	>99.9	69
6	C_6H_5-	H	rt	**Cat. 2c**	10	>99.9	91
7	2-Cl-C_6H_4	CH_3	0	**Cat. 2c**	18	>99.9	92
8	3-Cl-C_6H_4	CH_3	0	**Cat. 2c**	18	>99.9	93
9	4-Cl-C_6H_4	CH_3	0	**Cat. 2c**	18	>99.9	93
10	4-CH_3-C_6H_4	CH_3	0	**Cat. 2c**	18	>99.9	94
11	4-CH_3O-C_6H_4	CH_3	0	**Cat. 2c**	18	>99.9	94

[a] *Reaction conditions*: 1 atm H_2; 4 mg substrate; substrate concentration = 0.05 M in MeOH; substrate/catalyst = 100 (M/M).
[b] The conversion and ee values were determined by chiral GC with a 25 m×0.25 mm Chrompack Chirasil-L-Val column. The acids were converted to the corresponding methyl esters with methyl iodide/$KHCO_3$ before GC analysis. *R* configuration was obtained for all products. The absolute configuration was determined by comparing the retention time with that reported in the literature (Ref. 10).

gave **5** in 79–92% ee[3b,11] while the [Rh-(*R*)-BINAP$(CH_3OH)_2$]ClO_4 catalyst exhibited an opposite sense of asymmetric induction to give enantiomeric **6** with ees of 92–100% (Scheme 2).[12] In this study, it was of interest to note that the products of hydrogenations catalyzed by Rh and Ru complexes of the same chiral dipyridylphosphine ligand, such as (*R*)-**Cat. 1c** and (*R*)-**Cat. 2c**, were of the same absolute configurations (Table 2, entry 4 and Table 4, entry 5).

3. Conclusions

The effectiveness of chiral dipyridylphosphine ligands **1**–**3** in the Ru- and Rh-catalyzed asymmetric hydrogenation of methyl (*Z*)-2-acetamidocinnamate and their derivatives has been examined. The results demonstrated that the electronic and steric properties of these ligands have significant influences on their enantioselectivities. In addition, these ligands exhibited different catalytic properties and trends when different transition metal ions were used in the asymmetric hydrogenation.



4 **5** **6**

Scheme 2.

4. Experimental

4.1. General and materials

All manipulations with air-sensitive reagents were carried out under a dry nitrogen atmosphere using standard Schlenk techniques or in a nitrogen-filled MBRAUN Lab Master 130 glovebox. The hydrogenation reactions were performed in a 50 mL stainless-steel autoclave from Parr company. ^{1}H NMR and ^{31}P NMR were recorded in $CDCl_3$ on a Varian AS 500 at room temperature, and the chemical shifts were expressed in ppm. Gas chromatographic analyses were conducted on a HP 4890A or HP 5890 series II system. Optical rotations were measured on a Perkin–Elmer model 341 polarimeter. Commercial reagents were used as received without further purification unless otherwise stated. All solvents used were dried using standard, published methods and were distilled before use. Optically pure P-Phos (**1**), Tol-P-Phos (**2**) and Xyl-P-Phos (**3**) were synthesized according to our previously reported procedures[5–7] and their optical purities were determined by HPLC analysis using a Hewlett–Packard model HP 1050 LC interfaced to an HP 1050 series computer workstation.[5–7]

4.2. Synthesis of Ru(*R*-1)(C_6H_6)Cl_2, Cat. 1a

$[RuCl_2(C_6H_6)]_2$ (100 mg, 0.2 mmol) and (*R*)-P-Phos ((*R*)-**1**, 264 mg, 0.42 mmol) were placed in a 100 mL round-bottomed Schlenk flask. After the air in the flask was replaced by N_2, dried and degassed ethanol (48 mL) and benzene (6 mL) were added respectively by syringe. The mixture was stirred under N_2 at 50–60°C for 1 h to form a clear brownish yellow brown solution. After the solution was cooled to room temperature, the insoluble solid was filtered off and the solvent was evaporated under vacuum to give a yellowish green solid **Cat. 1a** (257 mg, 72%). ^{1}H NMR ($CDCl_3$, 500 MHz): δ 3.56 (s, 3H, OCH_3), 3.66 (s, 3H, OCH_3), 3.67 (s, 3H, OCH_3), 3.80 (s, 3H, OCH_3), 5.85 (s, 6H, C_6H_6), 5.99 (d, $J=10$ Hz, 1H, Py*H*), 6.49 (d, $J=10.5$ Hz, 1H, Py*H*), 7.21–7.83 (m, 20H, Ph*H*). ^{31}P NMR ($CDCl_3$, 202 MHz): δ 32.36 (d, $J=62.82$ Hz), 39.49 (d, $J=62.82$ Hz).

4.3. Synthesis of Ru(*R*-2)(C_6H_6)Cl_2, Cat. 1b

Cat. 1b was synthesized in 74% yield and characterized according to our previously reported procedures.[6]

4.4. Synthesis of Ru(*R*-3)(C_6H_6)Cl_2, Cat. 1c

Cat. 1c was synthesized in 69% yield according to the same procedure as in the preparation of **Cat. 1a**. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 2.24–2.39 (m, 24H, PhCH_3), 3.48 (s, 3H, OCH_3), 3.59 (s, 3H, OCH_3), 3.64 (s, 3H, OCH_3), 3.75 (s, 3H, OCH_3), 5.65 (s, 6H, C_6H_6), 5.96 (d, $J=11$ Hz, 1H, Py*H*), 6.46 (d, $J=10.5$ Hz, 1H, Py*H*), 6.74–7.29 (m, 12H, Ph*H*). ^{31}P NMR ($CDCl_3$, 202 MHz): δ 33.49 (d, $J=62.9$ 1 Hz), 39.96 (d, $J=62.51$ Hz).

4.5. Preparation of a stock solution of [Rh(*R*-1)(COD)]-BF_4, Cat. 2a

Under a nitrogen atmosphere, (*R*)-**1** (3.4 mg, 0.0053 mmol) was dissolved in methanol (1 mL). A solution of $[Rh(COD)_2]BF_4$ (2.1 mg, 0.005 mmol) in methanol (1 mL) was added dropwise to the above solution with stirring. The reaction mixture was stirred overnight to give a methanolic solution of [Rh(*R*-**1**)(COD)]BF_4 (**Cat. 2a**, 0.0025 mol L^{-1}). ^{31}P NMR (MeOH, 202 MHz): δ 21.1 (d, $J_{Rh-P}=144.8$ Hz).

4.6. Preparation of a stock solution of [Rh(*R*-2)(COD)]-BF_4, Cat. 2b

A stock solution of **Cat. 2b** was prepared in a similar fashion as that of **Cat. 2a**. ^{31}P NMR (MeOH, 202 MHz): δ 19.7 (d, $J_{Rh-P}=145.0$ Hz).

4.7. Preparation of a stock solution of [Rh(*R*-3)(COD)]-BF_4, Cat. 2c

A stock solution of **Cat. 2c** was prepared in a similar fashion as that of **Cat. 2a**. ^{31}P NMR (MeOH, 202 MHz): δ 21.2 (d, $J_{Rh-P}=144.6$ Hz).

4.8. Typical procedure for the asymmetric hydrogenation of methyl (*Z*)-2-acetamidocinnamate

A solution of 1.73×10^{-3} mol L^{-1} **Cat. 1a** in methanol (106 μL, 1.83×10^{-4} mmol) and a 0.183 mol L^{-1} methyl (*Z*)-2-acetamidocinnamate solution in methanol (100 μL, 0.0183 mmol) were charged to a 25 mL round-bottomed flask equipped with a magnetic stirring bar under a nitrogen atmosphere. A stream of H_2 was bubbled through the solution while it was magnetically stirred at ambient temperature for 3 h. The resulting solution was then submitted to analysis to determine the conversion and enantiomeric excess. Quantitative conversion of the starting material to the hydrogenation product, (*R*)-2-acetamido-3-phenyl-propanoste, with 90% ee was observed by chiral GC analysis (column, Chrompack Chirasil-L-Val, 25 m×0.25 mm, carrier gas, N_2).

Acknowledgements

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References

1. (a) Noyori, R. *Asymmetric Catalysis in Organic Synthesis*; Wiley: New York, 1994; Chapter 2; (b) Ojima, I. *Catalytic Asymmetric Synthesis*; 2nd ed.; Wiley: New York, 2000; pp. 9–17; (c) Nacobsen, E. N. Pfaltz, A.;

Yamamoto, H. *Comprehensive Asymmetric Catalysis*; Springer: Berlin, 1999; Vol. 1, Chapter 5.1; (d) Lin, G.-Q.; Li, Y.-M.; Chan, A. S. C. *Principles and Applications of Asymmetric Synthesis*; Wiley: New York, 2001; pp. 334–339.

2. Brown, J. M.; Chaloner, P. A. *J. Chem. Soc., Chem. Commun*. **1978**, 321.
3. (a) Ikariya, T.; Ishii, Y.; Kawano, H.; Arai, T.; Saburi, M.; Yoshikawa, S.; Akutagawa, S. *J. Chem. Soc., Chem. Commun*. **1985**, 922; (b) Kawano, H.; Ikariya, T.; Ishii, Y.; Saburi, M.; Yoshikawa, S.; Uchida, Y.; Kumobayashi, H. *J. Chem. Soc., Perkin Trans. 1* **1989**, 1571.
4. James, B. R.; Pacheco, A.; Rettig, S. J.; Thorburn, I. S.; Ball, R. G.; Ibers, J. A. *J. Mol. Catal*. **1987**, *41*, 147.
5. (a) Chan, A. S. C.; Pai, C.-C. US Patent 5,886,182, 1999; (b) Pai, C.-C.; Lin, C.-W.; Lin, C.-C.; Chen, C.-C.; Chan, A. S. C.; Wong, W. T. *J. Am. Chem. Soc*. **2000**, *122*, 11513.
6. Wu, J.; Chen, H.; Zhou, Z.-Y.; Yeung, C.-H.; Chan, A. S. C. *Synlett* **2001**, 1050.
7. Wu, J.; Chen, H.; Kwok, W. H.; Lam, K. H.; Zhou, Z. Y.; Yeung, C. H.; Chan, A. S. C. *Tetrahedron Lett*. **2002**, *43*, 1539.
8. Wu, J.; Chen, H.; Kwok, W. H.; Guo, R. W.; Zhou, Z. Y.; Yeung, C. H.; Chan, A. S. C., *J. Org. Chem*., to be published.
9. Mashima, K.; Kusano, K.; Sato, N.; Matsumura, Y.; Nozaki, K.; Kumobayashi, H.; Sayo, N.; Hori, Y.; Ishizaki, T.; Akutagawa, S.; Takaya, H. *J. Org. Chem*. **1994**, *59*, 3064.
10. Chan, A. S. C.; Hu, W.; Pai, C.-C.; Lau, C.-P.; Jiang, Y.; Mi, A.; Yan, M.; Sun, J.; Lou, R.; Deng, J. *J. Am. Chem. Soc*. **1997**, *119*, 9570.
11. Noyori, R.; Ikeda, T.; Ohkuma, T.; Widhalm, M.; Kitamura, M.; Takaya, H.; Akutagawa, S.; Sayo, N.; Saito, T.; Taketomi, T.; Kumoba-yashi, H. *J. Am. Chem. Soc*. **1989**, *111*, 9134.
12. (a) Miyashita, A.; Yasuda, A.; Takaya, H.; Toriumi, K.; Ito, T.; Souchi, T.; Noyori, R. *J. Am. Chem. Soc*. **1980**, *102*, 7932; (b) Miyashita, A.; Takaya, H.; Souchi, T.; Noyori, R. *Tetrahedron* **1984**, *40*, 1245.