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Cationic rhodium complexes with chiral tetradentate ligands as catalysts for enantioselective reduction of simple ketones

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Abstract

The interaction of $[Rh(COD)Cl]_2$ with two equivalents of (*S*)-N,N′-bis[*o*-(diphenylphosphino)benzylidene]propane-1,2-diamine [(*S*)-**1**] or (*S*)-N,N′-bis[*o*-(diphenylphosphino)benzyl]propane-1,2-diamine [(*S*)-**2**] in benzene/methanol mixture and then precipitation by the addition of a solution of NH_4PF_6 in water afforded cationic rhodium(I) complexes $[Rh(S)\text{-}MeP_2N_2][PF_6]$ and $[Rh(S)\text{-}MeP_2(NH)_2][PF_6]$ in good yield, respectively. Complexes $[Rh(R,R)\text{-}C_6P_2N_2][PF_6]$ and $[Rh(R,R)\text{-}C_6P_2(NH)_2][PF_6]$ were also prepared by an analogous manner. All these rhodium complexes have been characterized by analytical and spectroscopic methods and their asymmetric catalytic properties for enantioselective transfer hydrogenation of acetophenone have been tested. $[Rh(R,R)\text{-}C_6P_2(NH)_2][PF_6]$ was used as an excellent catalyst precursor for enantioselective transfer reduction of acetophenone in 2-propanol, leading to 2-phenylathanol in 97% yield and in 91% *ee* after 7 h at 83°C.

Keywords: Cationic rhodium complexes; Enantioselective reduction; Simple ketones

1. Introduction

Highly enantioselective hydrogenation of simple ketones without any other functionality is difficult to realize. Recently, asymmetric hydrogen transfer hydrogenation of simple ketones with 2-propanol or $HCOOH/Et_3N$ catalyzed by the Ru(II), Rh(I) or Ir(I) complexes with various chiral ligands has been developed with great successes [1–3].The Ru complexes with nitrogenous ligands are proved to be efficient catalyst precursors with up to 98% *ee* [4–7]. Generally, rhodium complexes with phosphine ligands are considered the most active catalysts for the hydrogenation, however, in the field of enantioselective transfer hydrogenation of simple ketones, most of the chiral Rh complexes afforded moderate to good enantioselectivity [8,9]. So far, only three papers have described the Rh(III) complexes containing monotosylated diamine ligands to give excellent enantioselectivity [10–

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12]. On this consideration, we have made an effort to design and synthesize Rh complexes with new chiral tetradentate diamine/diphosphine ligands as catalyst precursors for asymmetric reduction of simple ketones. On the other hand, we have recently reported a number of new chiral diamine/diphosphine PNNP-type ligands, which have been proved to be excellent chiral auxillaries for the asymmetric transfer hydrogenation of aromatic ketones with up to 97% *ee* [13–15]. In this paper, we wish to describe the designed synthesis of new chiral Rh(I) complexes containing chiral PNNP-type ligands and its use in the enantioselective reduction of acetophenone.

2. Experimental

2.1. General

All experiments were carried out in a nitrogen atmosphere with Schlenk and syringe techniques. All solvents were dried and purified according to standard methods before use. IR spectra were recorded on a PE-Spectroy 2000 spectrophotometer. NMR spectra were recorded on a Varian Unity-500 spectrometer. ^{1}H NMR chemical shifts are reported in ppm relative to TMS. ^{31}P spectra were referenced to 85% H_3PO_4 as external standard. The element analysis were carried out on a Fisons EA 1110. All melting points were measured in sealed tubes and were not corrected. The tetradentate diamine/diphosphine ligands (*S*)-**1**, (*S*)-**2**, (*R*,*R*)-**5** and (*R*,*R*)-**6** were prepared by previous reported methods [13–15].

2.2. Typical procedure for asymmetric transfer hydrogenation of ketones

The catalyst precursor (0.01 mmol) was added to a Schlenk tube and 2-propanol (20 ml) and *iso*-PrOK/*iso*-PrOH solution (0.1 M, 0.1 ml) were introduced under nitrogen. The mixture was stirred for 10 min, acetophenone was added and the solution was stirred at the desired temperature for the required reaction time. At the end of the experiment, the reaction products were determined by GLC analysis using a chiral chrompack CP-cyclodextrin-β-236-M-19 column.

2.3. Synthesis of [Rh(S)-MeP$_2$N$_2$][PF$_6$], [(S)-3][PF$_6$]

To a mixture of (*S*)-**1** (0.19 g, 0.30 mmol) and $[Rh(COD)Cl]_2$ (0.074 g, 0.15 mmol) were added benzene (6 ml) and methanol (6 ml). The mixture was stirred at room temperature for 12 h. After removal of solvent, the residue was dissolved in a minimum of methanol and precipitated by addition of a solution of NH_4PF_6 (0.082 g, 0.5 mmol) in H_2O (3 ml). The precipitate was collected and washed successively with H_2O (3 ml × 3) and diethyl ether (3 ml), then dried in vacuo to afford [(*S*)-**3**][PF_6] as a yellow solid (0.19 g, 73% yield). m.p. 240°C (dec.); Anal. Calcd. for $C_{41}H_{36}N_2F_6P_3Rh \cdot H_2O$: C, 55.67; H, 4.64; N, 3.18. Found C, 55.33; H, 4.15; N, 3.27. IR (KBr, cm^{-1}): 3412s, 3057m, 2931m, 1634m, 1589m, 1437s, 1167s, 1120vs, 998w, 750s, 699s, 545vs, 483w. ^{1}H NMR ($CDCl_3$): δ 8.75 (d, 2H, $J = 4.2$ Hz, PhCH═N), 6.82–7.35 (m, 28H, C_6H_5-), 3.35 (m, 2H, CH_2), 0.88 (d, 3H, CH_3). ^{31}P NMR ($CDCl_3$): δ 39.05, 38.39.

2.4. Synthesis of [Rh(S)-MeP$_2$(NH)$_2$][PF$_6$], [(S)-4][PF$_6$]

The procedure was similar to that of [(*S*)-**3**][PF_6], except that (*S*)-**2** (0.19 g, 0.15 mmol) and $[Rh(COD)Cl]_2$ (0.074 g, 0.15 mmol) were used, [(*S*)-**4**][PF_6] as a yellow solid was obtained (0.18 g, 70% yield). m.p. 231°C (dec.); Anal. Calcd. for $C_{41}H_{40}N_2F_6P_3Rh$: C, 56.56; H, 4.64; N, 3.22; Found C, 56.60; H, 4.65; N, 3.32. IR (KBr, cm^{-1}): 3400s, 3057m, 2931m, 1480w, 1436s, 1126s, 1093vs, 998w, 750s, 697s, 541s, 466w. ^{1}H NMR ($CDCl_3$): δ 6.85–7.63 (m, 28H, C_6H_5-), 3.94 (d, 2H, $J = 13.5$

Hz, PhCH −), 3.87 (d, 2H, $J = 18.5$ Hz, $PhCH_2-$), 2.54 (m, 1H, CH), 2.38 (m, 1H, CH_2), 2.29 (m, 1H, CH_2), 2.05 (br, 2H, NH), 0.84 (m, 3H, CH_3). ^{31}P NMR ($CDCl_3$): δ 33.09, 32.00.

2.5. Synthesis of [Rh(R, R)-CycloC$_6$P$_2$N$_2$]-[PF$_6$], [(R,R)-7][PF$_6$]

[(*R*,*R*)-**7**][PF_6] was prepared from [(*R*,*R*)-**5**] and [Rh(COD)Cl]$_2$ in accordance with the procedure for the [(*S*)-**3**][PF_6]. [(*R*,*R*)-**7**][PF_6] as a yellow solid was isolated (0.20 g, 74% yield). m.p. 245°C(dec.). Anal. Calcd. for $C_{44}H_{40}N_2F_6P_3Rh \cdot H_2O$: C, 57.15; H, 4.59; N, 3.03; Found C, 56.85; H, 4.85; N, 2.87. IR (KBr, cm^{-1}): 3414m, 3055m, 2931m, 2857w, 1630m, 1555w, 1435s, 1177m, 1099s, 750m, 696vs, 570w, 536vs. ^{1}H NMR ($CDCl_3$): δ 8.69 (d, 2H, $J = 4.0$ Hz, PhCH═N), 6.80–7.75 (m, 28H, C_6H_5-), 3.12 (m, 2H, CH), 1.66 (d, 2H, $J = 8.0$ Hz, CH_2), 1.46 (m, 2H, CH_2), 1.24 (m, 2H, CH_2). ^{31}P NMR ($CDCl_3$): δ 39.60.

2.6. Synthesis of [Rh(R,R)-CycloC$_6$P$_2$N$_2$H$_4$][PF$_6$], [(R,R)-8][PF$_6$]

In a similar fashion as described for [(*S*)-**3**][PF_6], [(*R*,*R*)-**8**][PF_6] as a yellow solid was obtained (0.19 g, 70% yield). m.p. 238°C(dec.). Anal. Calcd. for $C_{44}H_{44}N_2F_6P_3Rh \cdot 2H_2O$: C, 55.84; H, 5.28; N, 2.91; Found C, 55.83; H, 5.11; N, 2.96. IR (KBr, cm^{-1}): 3414m, 3056m, 2857w, 1591w, 1482w, 1436s, 1167m, 1098s, 750m, 723m, 697vs, 541vs, 464w. ^{1}H NMR ($CDCl_3$): δ 6.52–7.82 (m, 28H, C_6H_5-), 4.86 (m, 2H, $PhCH_2$), 4.36 (m, 2H, $PhCH_2$), 4.01 (d, 2H, $J = 10$ Hz, CH), 3.19 (s, 2H, CH_2), 2,17 (br, 2H, NH), 1.77 (d, 2H, $J = 28.5$ Hz, CH_2), 1.21 (m, 4H, CH_2). ^{31}P NMR ($CDCl_3$): δ 33.03.

2.7. Synthesis of [Rh(R,R)-CycloC$_6$P$_2$(NH)$_2$][ClO$_4$], [(R,R)-8][ClO$_4$]

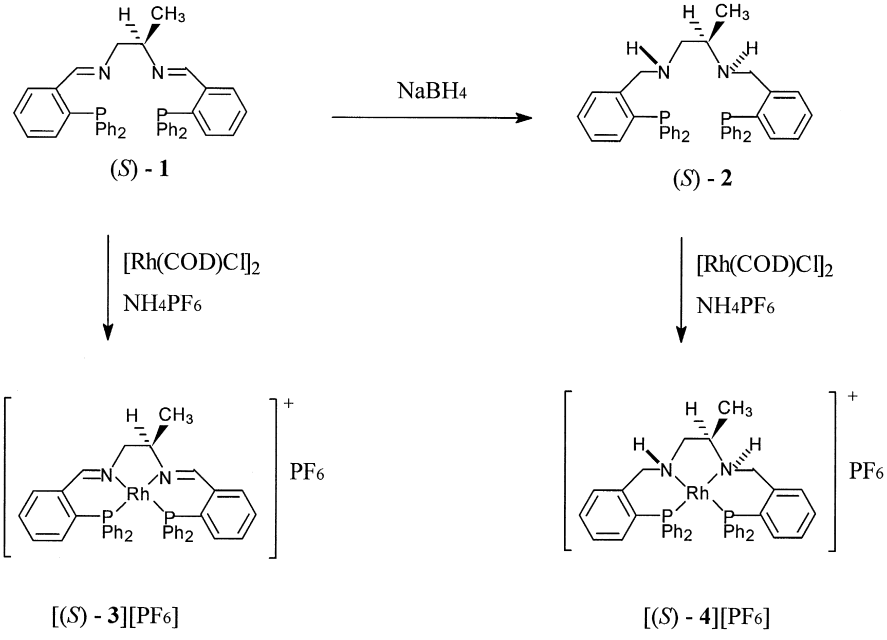
[(*R*,*R*)-**8**][ClO_4] was prepared by means of the above similar procedures, using $NaClO_4$ instead of NH_4PF_6, [(*R*,*R*)-**8**][ClO_4] as a yellow solid was obtained (0.2 g, 77% yield). m.p. 116°C (dec.). Anal. Calcd. for $C_{44}H_{44}N_2O_4ClP_2Rh \cdot C_6H_{14}$: C, 63.12; H, 6.16; N, 2.95; Found C, 63.66; H, 5.72; N, 2.75. IR (KBr, cm^{-1}): 4324m, 3056m, 2933m, 2858w, 1590w, 1436m, 1159m, 1094vs, 751m, 697s, 629w, 524s, 467w. ^{1}H NMR ($CDCl_3$): δ 6.82–7.62 (m, 28H, C_6H_5-), 4.00 (m, 2H, $PhCH_2$), 3.89(m, 2H, $PhCH_2$), 3.83 (d, 2H, $J = 13.5$ Hz, CH_2), 2.15 (d, 2H, $J = 8.5$ Hz, CH), 2.02 (m, 2H, NH), 1.60 (d, 2H, $J = 8.5$ Hz, CH_2), 1.10 (m, 2H, CH_2),0.89 (m, 2H, CH_2). ^{31}P NMR ($CDCl_3$): δ 32.81.

3. Results and discussion

3.1. Preparation of [(S)-3][PF$_6$] and [(S)-4][PF$_6$]

The interaction of [Rh(COD)Cl]$_2$ with two equivalents (*S*)-**1** or (*S*)-**2** in a 1:1 mixture of benzene-methanol for 12 h and precipitation by the addition of a NH_4PF_6 in water gave pale yellow solid [(*S*)-**3**][PF_6] and [(*S*)-**4**][PF_6] in 73% and 70% yield, respectively. The IR spectrum of [(*S*)-**3**][PF_6] exhibited a strong $\nu_{C=N}$ absorption at 1634 cm^{-1} for imino groups. The ^{1}H NMR spectrum of [(*S*)-**3**][PF_6] gave a doublet ($J_{P-H} = 4.2$ Hz) at 8.75 for the imino *H*C═N protons. The ^{31}P NMR spectrum of [(*S*)-**3**][PF_6] presented two singlets of equal intensity at δ 38.39 and 39.05, indicating that the two phosphino groups were coordinated and non-equivalent.

The ^{1}H NMR spectrum of [(*S*)-**4**][PF_6] presented two doublets of equal intensity at δ 3.94 for the $PhCH_2-$ protons; and a broad singlet at δ 2.05 for the –NH protons. The ^{31}P NMR spectrum of [(*S*)-**4**][PF_6] also exhibited two singlets of equal intensity at δ 32.00 and 33.09, indicating that both phosphorus atoms of the ligand were coordinated and non-equivalent. These results suggest that the complexes [(*S*)-**3**][PF_6] and [(*S*)-**4**][PF_6] have similar structures (Scheme 1).



Scheme 1.

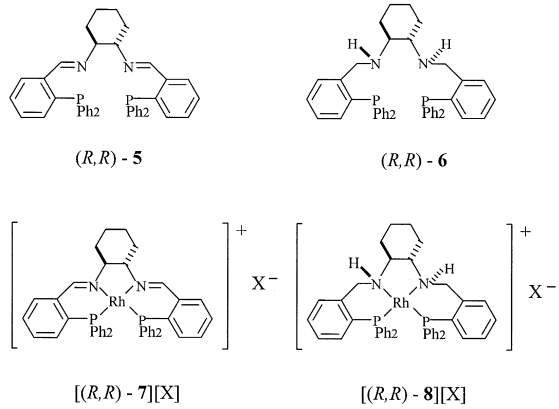
3.2. Preparation of [(R,R)-7][PF_6] and [(R,R)-8][PF_6]

When $[Rh(COD)Cl]_2$ was treated with two equimolars (R,R)-**5** or (R,R)-**6** in a 1:1 mixture of benzene/methanol for 12 h, and then precipitation by the addition of a NH_4PF_6 in water work up gave pale yellow solid $[(R,R)$-**7**$][PF_6]$ and $[(R,R)$-**8**$][PF_6]$ in 74% and 70% yield, respectively. The ^{1}H NMR of $[(R,R)$-**7**$][PF_6]$ exhibited a doublet ($J_{P-H} = 4.0$) at δ 8.69 for the imino *H*C═N protons. A singlet at δ 39.60 for the two phosphino groups in the ^{31}P NMR spectrum indicated that both phosphorus atoms were coordinated to rhodium center and equivalent. The ^{1}H NMR spectrum of $[(R,R)$-**8**$][PF_6]$ gave two multiplets of equal intensity at δ 4.36 and 4.86 for the PhCH_2- protons. The ^{31}P NMR of $[(R,R)$-**8**$][PF_6]$ only presented a singlet at δ 33.03, suggesting that the two phosphorus atoms were coordinated and equivalent. Based on these spectroscopic data, the structures of $[(R,R)$-**7**$][PF_6]$ and $[(R,R)$-**8**$][PF_6]$ have been proposed as shown in Scheme 2.

3.3. Asymmetric transfer hydrogenation of aromatic ketones

3.3.1. Influence of various chiral rhodium complexes on the rate and enantioselectivity

Several chiral cationic rhodium complexes for asymmetric transfer hydrogenation of acetophenone have been tested and the results were listed in Table 1. The $[Rh(COD)Cl]_2/(R,R)$-**6**



Scheme 2.

Table 1
Influence of various chiral rhodium complexes on the reaction rate and enantioselectivity[a]

Entry	Catallyst	[ketone]:[Rh]:[*i*-PrOK]	Time (h)	Alcohol product		
				Yield (%)[b]	*ee* (%)[c]	Config[d]
1	$[Rh(COD)Cl]_2/(R,R)$-**6**[e]	100:1:1	9	56	36	*S*
2	$[Rh(COD)Cl]_2/(R)$-**2**[e]	100:1:1	9	13	25	*R*
3	$[Rh(S)\text{-}MeP_2N_2][PF_6]$	100:1:2	10	98	15	*S*
4	$[Rh(R,R)\text{-}C_6P_2N_2][PF_6]$	100:1:1	7	40	40	*S*
5	$[Rh(S)\text{-}MeP_2(NH)_2][PF_6]$	100:1:2	14	95	74	*S*
6	$[Rh(S)\text{-}MeP_2(NH)_2][PF_6]$	100:1:3	14	96	65	*S*
7	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	100:1:1	5	92	88	*R*
8	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	100:1:1	7	97	91	*R*

[a]Conditions — catalyst, 0.01 mmol; solvent: *iso*-PrOH, 20 ml; 83°C.
[b]GLC analysis.
[c]Capillary GLC analysis using a chiral Chromack CD-cyclodextrin-β-236-M-19 column unless otherwise specified.
[d]Determined by comparison of the retention times of the enantiomers on the GLC traces with literature values.
[e]In 1:1 of mole ratio.

or $[Rh(COD)Cl]_2/(S)$-**2** system showed only low conversion and enantioselectivity (entries 1 and 2). When rhodium complexes containing tetradentate diiminodiphosphine ligand, such $[Rh(S)\text{-}MeP_2N_2]$ and $[Rh(R,R)\text{-}C_6P_2N_2]$, as catalyst precursors were used, enantioselectivities were still low (entries 3 and 4). However, cationic rhodium complexes with diaminodiphosphine ligand, high conversion and *ee* were observed (entries 5–8). These results indicated that the presence of an NH moiety in the ligands is important for obtaining high conversion and *ee* [2,7,15,16]. Moreover, $[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$ has been proved to be more effective catalyst and this complex was chosen for the test in this work.

3.3.2. Effects of the substrate and base concentration

The effect of the substrate and base concentration on reactivity and enantioselectivity was studied and the results are summarized in Table 2. Although the yields gradually decreased on increasing the mole ratios of [acetophenone]/[Rh] from 100:1 to 500:1, the enantioselectivity is still high (Table 2, entries 1–5), which means the catalyst can still be used to the systems with higher substrate concentration.

Table 2
Influence of the substrate and base concentration on reactivity and enantioselectivity[a]

Entry	Catalyst	[ketone]:[Rh]:[*i*-PrOK][b]	Time (h)	Alcohol product		
				Yield (%)	*ee* (%)	Config
1	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	100:1:1	7	97	91	*R*
2	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	200:1:1	12	86	87	*R*
3	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	300:1:1	16	81	89	*R*
4	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	400:1:1	24	85	89	*R*
5	$[Rh(S,S)\text{-}C_6P_2(NH)_2][PF_6]$	500:1:1	24	75	88	*R*
6	$[Rh(R,R)\text{-}C_6P_2(NH)_2][ClO_4]$	100:1:0.5	10	86	85	*S*
7	$[Rh(R,R)\text{-}C_6P_2(NH)_2][ClO_4]$	100:1:1	9	86	89	*S*
8	$[Rh(R,R)\text{-}C_6P_2(NH)_2][ClO_4]$	100:1:2	7	97	66	*S*
9	$[Rh(R,R)\text{-}C_6P_2(NH)_2][ClO_4]$	100:1:3	4	99	50	*S*
10	$[Rh(R,R)\text{-}C_6P_2(NH)_2][ClO_4]$	100:1:1.5	7	96	77	*S*

[a]Conditions — catalyst: 0.01 mmol; solvent: *iso*-PrOH, 20 ml; refluxing temperature; others as shown in Table 1.
[b]In mole ratio.

The concentration of base is an important factor for reaction rate and stereoselectivity. The catalytic system is inactive without the presence of *iso*-PrOK. The reaction rate increased with increase of the *iso*-PrOK concentration with the loss of enantiometric purity of the product (entries 6–10). The lower ratios for a [*iso*-PrOK] to [Rh] are necessary for obtaining high enantioselectivity.

3.3.3. Effect of reaction temperature

The influence of reaction temperature on conversion and stereoselectivity is shown in Fig. 1. The effect of temperature was remarkable and an increase of the temperature steeply rose the conversion. Generally, the increase of the temperature accelerates the reaction with somewhat loss of enantiomeric purity of the product. However, in the case of [(*S,S*)-**8**][PF_6] as catalyst precursor and under our experimental conditions, an increase of the temperature accelerates the reaction rate with the increase of enantioselectivity.

3.3.4. Evolution of the conversion and the enantioselectivity with reaction time

The evolution of the conversion and enantioselectivity with reaction time has been studied and the results are shown as in Fig. 2.

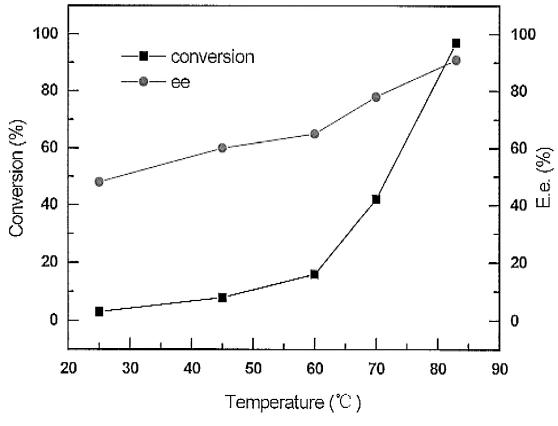


Fig. 1. Influence of reaction temperature on the conversion and the ee. Conditions — catalyst: [Rh(*S,S*)-$C_6P_2(NH)_2$][PF_6], 0.01 mmol; solvent: *iso*-PrOH, 20 ml; [acetophenone]:[[Rh]:[*iso*-PrOK] = 100:1:1; 24 h.

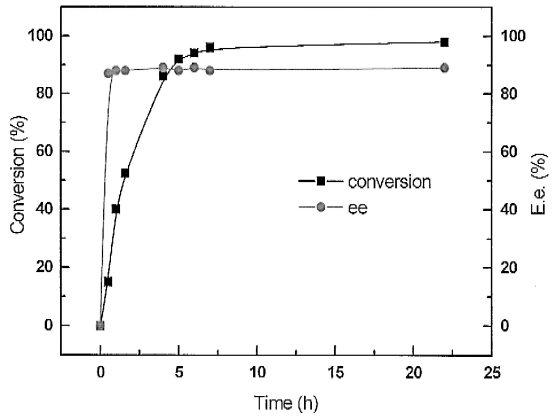


Fig. 2. The evolution of the conversion and the enantioselectivity with reaction time. Conditions — [Rh(*S,S*)-$C_6P_2(NH)_2$][PF_6], 0.01 mmol; [acetophenone]:[[Rh]:[*iso*-PrOK] = 100:1:1; 83°C.

The prolongation of reaction time generally leads to the increase of the conversion with the loss of the enantioselectivity. However, when the molar ratio of [acetophenone]/[Rh]/[*iso*-PrOK] was 100:1:1, the conversion sharply increased in up to 92% after reaction for 5 h at 83°C and then slightly rose with prolongation of reaction time; but the enantioselectivity remains constant with reaction time, probably, due to the strong rigidity of the rhodium complex.

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References

[1] G. Zassinovich, G. Mestroni, S. Gladiali, Chem. Rev. 92 (1992) 1051.
[2] R. Noyori, S. Hashiguchi, Acc. Chem. Res. 30 (1997) 97.
[3] M.J. Palmer, M. Wills, Tetrahedron: Asymmetry 10 (1999) 2045.
[4] A. Togni, L. Venanzi, Angew. Chem., Int. Ed. Engl. 33 (1994) 497.

[5] S. Hashiguchi, A. Fujii, J. Takehara, T. Ikariya, R. Noyori, J. Am. Chem. Soc. 117 (1995) 7562.
[6] A. Fujii, S. Hashiguchi, N. Uematsu, T. Ikariya, R. Noyori, J. Am. Chem. Soc. 118 (1996) 2521.
[7] Y. Jiang, Q. Jiang, X. Zhang, J. Am. Chem. Soc. 120 (1998) 3817.
[8] S. Gladiali, L. Pinna, A. Delogu, S.D. Martin, G. Zassinovich, G. Mestroni, Tetrahedron: Asymmetry 1 (1990) 635.
[9] P. Gamez, F. Fache, P. Mangency, M. Lemaire, Tetrahedron Lett. 34 (1993) 6897.
[10] K. Mashima, T. Abe, K. Tani, Chem. Lett. (1998) 1199.
[11] K. Mashima, T. Abe, K. Tani, Chem. Lett. (1998) 1201.
[12] K. Marata, T. Ikariya, R. Noyori, J. Org. Chem. 64 (1999) 2186.
[13] J.X. Gao, H.L. Wan, W.K. Wong, M.C. Tse, W.T. Wong, Polyhedron 15 (1996) 1241.
[14] P.P. Xu, J.X. Gao, Y.Q. Huang, H. Zhang, H.L. Wan, K.R. Tsai, T. Ikariya, Chem. Res. Chin. Univ. 14 (1998) 340.
[15] J.X. Gao, T. Ikariya, R. Noyori, Organometallics 15 (1996) 1087.
[16] P. Gamez, F. Fade, M. Lemaire, Tetrahedron: Asymmetry 6 (1995) 705.