The Asymmetric Homogeneous Hydrogenation of Olefins with the Rhodium Complexes of (1*S*,2*S*)-1,2-Bis(diphenylphosphinamino)cyclohexane and (2*S*,3*S*)-2,3-Bis(diphenylphosphinamino)butane

Ken-ichi Onuma,* Tomiyasu Ito, and Asao Nakamura

Central Research Laboratories, Ajinomoto Co., Inc., 1-1 Suzuki-cho, Kawasaki 210

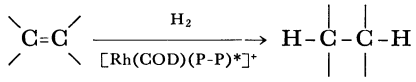
(Received September 22, 1979)

The effect of triethylamine on asymmetric hydrogenation has been studied using the cationic rhodium complex of (1*S*,2*S*)-1,2-bis(diphenylphosphinamino)cyclohexane or (2*S*,3*S*)-2,3-bis(diphenylphosphinamino)butane as a catalyst. By the addition of triethylamine, higher optical yields are achieved in the hydrogenation of (*Z*)-α-acetamidocinnamic acid and itaconic acid and higher conversion rates are obtained in the hydrogenation of (*E*)-2-methylcinnamic acid, mesaconic acid, and citraconic acid. The specific effect of triethylamine on the substrates with a carboxyl group may be explained by the ionization of the carboxyl group, which coordinates the catalytic rhodium complex firmly.

In recent years, the asymmetric hydrogenation of olefins has been successfully carried out with chiral phosphine–rhodium complexes.[1] It has been often observed that the addition of triethylamine improves the reactivity or the stereoselectivity of the asymmetric hydrogenation of olefins,[2] for which several explanations have been attempted. We would like to describe here the effect of triethylamine on the asymmetric hydrogenation of olefins with the rhodium complexes of (1*S*,2*S*)-1,2-bis(diphenylphosphinamino)cyclohexane, [(*S*,*S*)-I][3] and (2*S*,3*S*)-2,3-bis(diphenylphosphinamino)-butane, [(*S*,*S*)-II].[3b] The six olefins listed in Table 1 are adopted as the substrates. As the substrates have different substituents on the olefinic group, the effects of triethylamine on the hydrogenation of these compounds have been interpreted in terms of the structures of the substituents.

Results and Discussion

Either (*S*,*S*)-I or (*S*,*S*)-II was used as a chiral bisphosphine ligand in the catalytic precursor, [Rh(1,5-cyclooctadiene)(bisphosphine)]$^+ClO_4^-$.[4] The six olefins were hydrogenated with each of the rhodium complexes as shown below (Scheme 1). The product



Scheme 1.

was then isolated carefully, and the optical purity was determined. The results are shown in Table 1, together with some results obtained from a neutral *in situ* catalyst. As can be seen there, the cationic catalyst gave better results in both reactivity and stereoselectivity than the neutral catalyst. Therefore, the hydrogenation has been studied with the cationic catalyst.

Effect of Triethylamine. In the absence of triethylamine, (*Z*)-α-acetamidocinnamic acid (III) and itaconic acid (V) were hydrogenated quantitatively. *N*-(1-Phenyl-1-propenyl)acetamide (VIII) was hydrogenated with a conversion of 50%. The other substrates were hydrogenated with lower conversions. Therefore, as for the substituent on the ethylenic bond in the substrate, the acetamido and carboxymethyl groups are considered to play an important role in the hydrogenation. Recent studies[9] on the substrate structures show that an efficient asymmetric hydrogenation depends on the ability of the substrate to form a bidentate complex in the transition state and that the β-carbonyl group in the substituent of an olefin, –C=C–X–C(=O)– (X=NH, CH_2, O), is favorable for the chelate formation. The high conversion rate and optical yield for the hydrogenation of III and V support the importance of the presence of the β-carbonyl group.

The effect of the addition of triethylamine varies, depending on the substrate structures, as follows:

For the substrate with free carboxyl, but no β-carbonyl group of an olefin, *e.g.*, (*E*)-2-methylcinnamic acid (IV), mesaconic acid (VI), and citraconic acid (VII), the conversion rate increases upon the addition of triethylamine, to a particularly remarkable extent in VII. However, the optical yield is low in the presence of triethylamine. The optical yields could not be measured in the absence of triethylamine because of the low conversion rate. Therefore, the effect of triethylamine on the optical yield could not be examined.

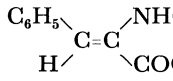
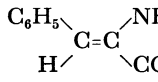
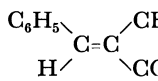
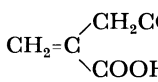
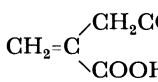
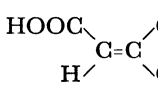
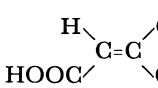
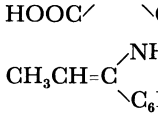
For a substrate with both free carboxyl and β-carbonyl groups, *e.g.*, III and V, the hydrogenation proceeds quantitatively irrespective of the presence of triethylamine. As far as the optical yield is concerned, the addition of triethylamine seems to have some favorable effect.

For the substrate with no free carboxyl but with a β-carbonyl group, VIII, the conversion rate rather decreases and the optical yield is not affected.

As has been mentioned above, the addition of triethylamine affects the conversion or the optical yield only in the hydrogenation of a substrate with a free carboxyl group. This implies that triethylamine may interact with the carboxyl group to ionize it and that the substrate may coordinate the catalytic rhodium complex more firmly.

On the addition of triethylamine, the optical yield increases in the hydrogenation of III and V. In the hydrogenation of IV, VI, and VII, however, the optical yield is low even if triethylamine is added. In the former cases, triethylamine is considered to make a chelating substrate–rhodium complex more rigid. In

TABLE 1. ASYMMETRIC HYDROGENATIONS[a] OF OLEFINS WITH CHIRAL AMINOPHOSPHINE-RHODIUM COMPLEXES

	Substrate	Et_3N[b]	(*S*,*S*)-I complex[c]			(*S*,*S*)-II complex[c]		
			S/Rh[d]	Conv.[e]	O.Y.[f]	S/Rh	Conv.	O.Y.
III		—	550	100%	72(*S*)%e.e.	540	100%	62(*S*)%e.e.
		+	550	100	83(*S*)			
		g) —	90	100	48(*S*)			
IV		—	140	12	h)	140	7	h)
		+	140	73	29(*S*)	150	49	14(*S*)
V		—	860	100	76(*R*)	860	100	48(*R*)
		+	850	100	85(*R*)	840	100	82(*R*)
		g) —	150	100	55(*R*)			
VI		—	170	5	h)			
		+	170	32	3(*S*)			
VII		—	430	0	h)	200	0	h)
		+	160	90	3(*S*)	190	95	1(*S*)
VIII		—	320	50	19(*S*)			
		+	320	24	20(*S*)			

a) Hydrogenation was carried out with 1 g of a substrate and a cationic rhodium complex in benzene/ethanol (v/v=1/1). b) The triethylamine-to-substrate molar ratio was 1.15. c) Catalytic precursor. (*S*,*S*)-I complex: [Rh(COD)(*S*,*S*)-I]$^+ClO_4^-$. (*S*,*S*)-II complex: [Rh(COD)(*S*,*S*)-II]$^+ClO_4^-$. d) Molar ratio of the substrate to the complex. e) Estimated by NMR analysis. f) Calculated on the basis of the reported value for the optically pure enantiomer as follows: (*S*)-2-methyl-3-phenylpropionic acid; $[\alpha]_D^{20}=+27.02°$ ($c=11.59$, C_6H_6).[5] (*R*)-methylsuccinic acid; $[\alpha]_D^{20}=+16.88°$ ($c=2.16$, EtOH).[6] (*S*)-*N*-(1-phenylpropyl)acetamide; $[\alpha]_D^{20}=-137.8°$ ($c=2.4$, MeOH).[7] *N*-acetyl-(*S*)-phenylalanine; $[\alpha]_D^{20}=+46.0$ ($c=1.0$, EtOH).[8] The predominant configuration of the product is shown in parentheses. g) Hydrogenations were carried out with an *in situ* catalyst. h) The optical rotation was not measured.

the latter cases, the lack of steric control may be caused by the non-rigid conformation of the substrate–rhodium complex because of the absence of the β-carbonyl group. The very low optical yield in VI and VII especially may be caused by the approximately symmetrical structure of the substrates, in which the deviation from the symmetry originates only from the difference in the substituents between the hydrogen and methyl groups.

Catalyst Studies. The (*S*,*S*)-I complex was expected to give a higher optical yield than the (*S*,*S*)-II complex, as the former had a more rigid conformation, restricted by the cyclohexane ring. However, the (*S*,*S*)-I complex gave a conversion rate and/or optical yields similar to those of the (*S*,*S*)-II complex for any of the substrate, as is shown in Table 1. Therefore, it may be concluded that the two complexes have similar reactivities and stereoselectivities.

The stereoselectivity of the catalytic rhodium complexes of (*S*,*S*)-I and (*S*,*S*)-II was compared with that of the other chiral rhodium catalysts, which make a similar seven-membered chelate ring with rhodium, as is shown in Fig. 1. The optical yields and the predominant configurations of the product of the asymmetric hydrogenation of (*Z*)-α-acetamidocinnamic acid

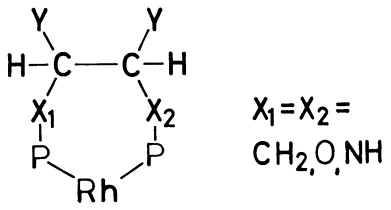


Fig. 1. The seven-membered chelate ring.

are as follows: 72% e.e. (*S*) for (*S*,*S*)-I, 70% e.e. (*R*) for (*R*,*R*)-I,[3b] 62% e.e. (*S*) for (*S*,*S*)-II, 94% e.e. (*S*) for (1*S*,2*S*)-1,2-bis(diphenylphosphinamino)-1,2-diphenylethane,[3a] 82% e.e. (*R*) for (*R*,*R*)-DIOP,[10] 68.5%e.e. (*S*) for (1*S*,2*S*)-1,2-bis(diphenylphosphinoxy)-cyclohexane,[11] 35%e.e. (*S*) for (1*S*,2*S*)-1,2-bis(diphenylphosphinomethyl)cyclohexane,[12] and 36% e.e. (*R*) for (1*R*,2*R*)-1,2-bis(diphenylphosphinomethyl)cyclohexane.[13] Thus the predominant configuration of the product may be supposed to be governed by the configuration arround the asymmetric carbons in the seven-membered ring for any of these eight complexes. That is, the complex with X_1 on the upper side and X_2 on the down side of the plane described in this paper would always give *N*-acetyl-(*S*)-phenylalanine

and the complex with X_1 on the down side and X_2 on the upper side would always give *N*-acetyl-(*R*)-phenylalanine. Therefore, the rhodium complexes with any one of the eight chiral ligands are considered to have essentially the same conformation, even if X is CH_2, NH, or O.

Experimental

General. The melting points were determined with a Yanagimoto melting-point-measuring apparatus, MP-S2. The NMR spectra were recorded on a Varian high-resolution NMR spectrometer, EM-390. The optical rotations were measured with a JASCO J-20 recording spectropolarimeter. The hydrogenations were carried out in a glass autoclave, EM-U-300, of Taiatsu Glass Industry.

Substrates and Solvents. The (*E*)-2-methylcinnamic acid (mp 80—81 °C) was obtained from Nakarai Chemicals. The itaconic acid (mp 162—164 °C dec), mesaconic acid (mp 204—205 °C), and citraconic acid (mp 98—99 °C) were obtained from Tokyo Kasei Industry. The *N*-(1-phenyl-1-propenyl)acetamide was prepared according to the procedure in the literature.[14] The α-acetamidocinnamic acid[15] was prepared by a standard Erlenmeyer procedure. The solvents for hydrogenation were purified as follows: the benzene was distilled, dried over sodium metal, degassed by means of the vacuum technique, and stored under argon; the ethanol was distilled, dried over a molecular sieve, degassed, and stored similarly.

Preparation of (S,S)-*I.* (1*S*,2*S*)-1,2-Cyclohexanediamine was prepared from D-(−)-tartaric acid according to the method of Asperger and Liu:[16] bp 79—81 °C (15 mmHg), $[\alpha]_D^{24}=+40.1°$ ($c=4.9$, C_6H_6). (1*S*,2*S*)-1,2-Cyclohexanediame (6.8 g) was dissolved in dry benzene (180 ml) and dried over NaOH pellets for several days. The benzene solution was transferred into the reaction flask, to which dry triethylamine (16.6 ml) was then added. Chlorodiphenylphosphine (26.4 g) was then added dropwise to the stirred solution at 10 °C. After the addition was complete, the resulting solution was stirred for 30 min at 20 °C. The solution was filtered and concentrated under reduced pressure. (*S*,*S*)-I was separated as crystals, which were recrystallized twice from benzene. 10.0 g. Mp 130—132 °C. $[\alpha]_D^{15}=+4.48°$ ($c=1.0$, C_6H_6). Found: C, 74.60; H, 6.68; N, 5.75; P, 12.50%. Calcd for $C_{30}H_{32}N_2P_2$: C, 74.67; H, 6.68; N, 5.81; P, 12.84%.

Preparation of (S,S)-*II.* (2*S*,3*S*)-2,3-Butanediamine was prepared according to the procedure of Dickey and his co-workers.[17] $[\alpha]_D^{29}=+29.0°$ ($c=3.23$, C_6H_6). (*S*,*S*)-II was prepared by the reaction of chlorodiphenylphosphine and (2*S*,3*S*)-2,3-butanediamine, much like (*S*,*S*)-I. Mp 83—85 °C. $[\alpha]_D^{15}=+2.98°$($c=0.5$, C_6H_6). Found: C, 73.44; H, 6.58; N, 6.09; P, 13.28%. Calcd for $C_{28}H_{30}N_2P_2$: C, 73.67; H, 6.62; N, 6.14; P, 13.57%.

Catalytic Precursors. The cationic rhodium complexes $[Rh(COD)(P\text{-}P)]^+ClO_4^-$ were prepared according to the method of Schrock and Osborn.[4] $[Rh(COD)Cl]_2$ (576 mg) and sodium perchlorate (400 mg) were placed in acetone (4 ml). (*S*,*S*)-I (1.13 g) was then slowly stirred in. Stirring was continued for 5 min, and then dichloromethane (20 ml) was added. The suspension was filtered and washed with dichloromethane. The filtrate was concentrated to *ca.* 5 ml under reduced pressure and then left at room temperature. The wine-red crystals were filtered off, washed with diethyl ether, and air-dried. The yield of the product was 1.46 g. The crystals were solvated with dichloromethane as detected by NMR (δ 5.30 ppm). $[Rh(COD)(S,S)\text{-}I]^+ClO_4^-\cdot 1/2CH_2Cl_2$; mp 142—145 °C (dec); Found: C, 55.38; H, 5.55; N, 3.21%. Calcd for $RhC_{38}H_{44}N_2P_2ClO_4\cdot 1/2CH_2Cl_2$: C, 55.34; H, 5.43; N, 3.35%. The rhodium complex of (*S*,*S*)-II was prepared by the same procedure. The crystals were also solvated with dichloromethane. $[Rh(COD)(S,S)\text{-}II]^+ClO_4^-\cdot 1/2CH_2Cl_2$; mp 143—144 °C (dec); Found: C, 54.02; H, 5.45; N, 3.38%. Calcd for $RhC_{36}H_{42}N_2P_2ClO_4\cdot 1/2CH_2Cl_2$: C, 54.15; H, 5.35; N, 3.46%. These rhodium complexes were stored in an ampoule under argon.

Hydrogenation Procedure. A substrate (1 g), one of the cationic rhodium complexes, ethanol, and benzene were placed in the glass autoclave under argon. The rhodium complex was dissolved completely. In the case of the addition of triethylamine, triethylamine was added at this stage. Hydrogen was then admitted into the autoclave. After the hydrogenation was complete, the solution was filtered and evaporated to dryness. The conversion rate of the substrate was determined by NMR at this stage. For the isolation of the hydrogenation product, either one of the following methods was applied. Method 1: For α-methylsuccinic acid in the absence of triethylamine and *N*-(1-phenylpropyl)acetamide, the product was separated from the insoluble catalyst by extraction with water and by concentration. Method 2: For other cases, the product was dissolved in 0.5 mol dm^{-3} NaOH. The resulting solution was acidified with dilute HCl and repeatedly extracted with a mixed solvent of ether and dichloromethane (v/v= 1/4). The organic layer was dried over anhydrous sodium sulfate and evaporated to dryness.

References

1) D. Valentine, Jr., and J. W. Scott, *Synthesis*, **5**, 329 (1978), and the references cited therein.

2) a) W. S. Knowles, M. J. Sabacky, and B. D. Vineyard, *Ann. N. Y. Acad. Sci.*, **172**, 232 (1970); G. Descotes, D. Lafont, and D. Sinou, *J. Organometal. Chem.*, **150** (1978) c14; b) K. Achiwa, *J. Am. Chem. Soc.*, **98**, 8265 (1976); c) I. Ojima, and T. Kogure, *Chem. Lett.*, **1978**, 567.

3) a) M. Fiorini and G. M. Giongo, *J. Mol. Catal.*, **5**, 303 (1979); b) K. Onuma, T. Ito, and A. Nakamura, *Chem. Lett.*, **1979**, 905; c) K. Hanaki, K. Kashiwabara, and J. Fujita, 28th Symposium on Coordination Chemistry, Japan (Matsuyama), 1978, Abstracts 2A07.

4) R. R. Schrock and J. A. Osborn, *J. Am. Chem. Soc.*, **93**, 2397 (1971).

5) A. M. Aguiar, C. J. Morrow, J. D. Morrison, R. E. Burnett, and W. F. Masler, *J. Org. Chem.*, **41**, 1545 (1976).

6) E. Berner and R. Leonardsen, *Ann.* **538** 1 (1939).

7) A. La Manna, V. Chislande, O. B. Hulbert, and O. M. Scope, *Farmaco Ed., Sci.*, **22**, 1037 (1967).

8) M. D. Fryzuk and B. Bosnich, *J. Am. Chem. Soc.*, **99**, 6262 (1977).

9) a) J. Halpern, Symposium on Rhodium in Homogeneous Catalysis, Veszprem Hungary (1978), p. 30; b) W. C. Christopfel and B. D. Vineyard, *J. Am. Chem. Soc.*, **101**, 4406 (1979); c) J. M. Brown and P. A. Chaloner, *Tetrahedron Lett.*, **1978**, 1877; d) G. Gelbard and H. B. Kagan, *Tetrahedron*, **32**, 233 (1976).

10) H. B. Kagan and T. P. Dang, *J. Am. Chem. Soc.*, **94**, 6249 (1972).

11) M. Tanaka and I. Ogata, *J. Chem. Soc., Chem. Commun.*, **1975**, 735.

12) R. Glaser, M. Twaik, S. Geresh, and J. Blumenfeld,

Tetrahedron Lett., **1977**, 4635.
13) P. Aviron-Violet, Y. Colleuille, and J. Varagnat, *J. Mol. Catal.*, **5**, 41 (1979).
14) Y. H. Suen, A. Horeau, and H. B. Kagan, *Bull. Soc. Chim. Fr.*, **1965**, 1454.
15) R. M. Herbst and D. Shemin, *Org. Synth.*, Coll. Vol. 2, 1 (1943).
16) R. G. Asperger and C. F. Liu, *Inorg. Chem.*, **4**, 1493 (1965).
17) F. H. Dickey, W. Fickett, and H. J. Lucas, *J. Am. Chem. Soc.*, **74**, 944 (1952).