Steric and Electronic Effects of Substrates and Rhodium Chiral Catalysts in Asymmetric Cyclopropanation[1)]

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We have prepared several new, efficient, chiral *N*-acyl pyrrolidine carboxylic acid ligands for dirhodium-catalyzed asymmetric cyclopropanation and found that the steric and electronic effects of the rhodium(II) complexes and substrates influenced the enantioselectivity and catalytic activity. These electron-rich catalysts were shown to be efficient for asymmetric cyclopropanation using 1-chloro-1-fluoroethylene as a substrate.

Key words catalytic asymmetric cyclopropanation; rhodium complex; vinyldiazomethane; chiral *N*-acyl pyrrolidine; 1-chloro-1-fluoroethylene; styrene

Asymmetric cyclopropanations catalyzed by rhodium(II)–chiral carboxylate or acetamidate complexes have been reported by many groups[2)] and these complexes are efficient catalysts for diastereoselective cyclopropanation using the chiral source in amounts equimolar with substrates. But, in almost all cases, low enantioselectivities were obtained when the amount of the chiral source was less than equimolar.

We have already proposed a new design concept[3)] for developing chiral bisphosphine–rhodium(I) complexes as asymmetric hydrogenation catalysts that are highly efficient in terms of enantioselectivity and catalytic activity. In order to design rhodium(II)-chiral carboxylate catalysts which are efficient for asymmetric cyclopropanation in terms of reactivity and enantioselectivity, we prepared several new chiral ligands which differ in electronic and steric factors. That is to say, they were designed based on L-proline as a fundamental skeleton while varying the steric and electronic factors of the *N*-substituent, which were thought to be important for asymmetric control. The rhodium(II)-complexes **3a**—**j** were synthesized as shown in Chart 1.

Each *N*-acyl L-proline was prepared by *N*-acylation of L-proline benzyl ester with acyl halide in the presence of *N*,*N*-diisopropylethylamine, followed by debenzylation by hydrogenolysis. Each rhodium(II)–ligand complex was prepared by treating rhodium trichloride with the appropriate carboxylate salt in ethanol and H_2O.[4)] The structures of these complexes were determined by ^{1}H-NMR analysis and elemental analysis. Davies and Hutcheson reported a new chiral *N*-sulfonyl-substituted proline, the rhodium(II) complex of which was revealed to be an efficient catalyst in the asymmetric cyclopropanation of styrene with vinyldiazomethane.[5)] So we carried out the asymmetric cyclopropanation of styrene and some other olefins bearing an electron-donating or -withdrawing group with vinyldiazomethane catalyzed by **3a**—**j** and rhodium(II)–chiral *N*-sulfonyl-substituted proline complex for comparison of their efficiency.

Table 1 summarizes the results of the asymmetric cyclopropanation of styrene with Methyl (*E*)-2-diazo-4-phenyl-3-butenoate.

Yield was determined by GC analysis using *cis*-decalin as an internal standard. ^{1}H-NMR analysis suggested that only *E* cyclopropane was generated and the absolute configuration of the major enantiomer was determined by comparing the optical rotation value with the reported optical rotation.[6)] As can be seen (entries **3a**—**f**), the combined electron-donating and steric effects (*ortho*-, *para*-, or *meta*-substitution) resulted in variation of the yields from 43% to 91% and the enantioselectivity from 7% to 76% ee. But the rhodium(II)–complex bearing a

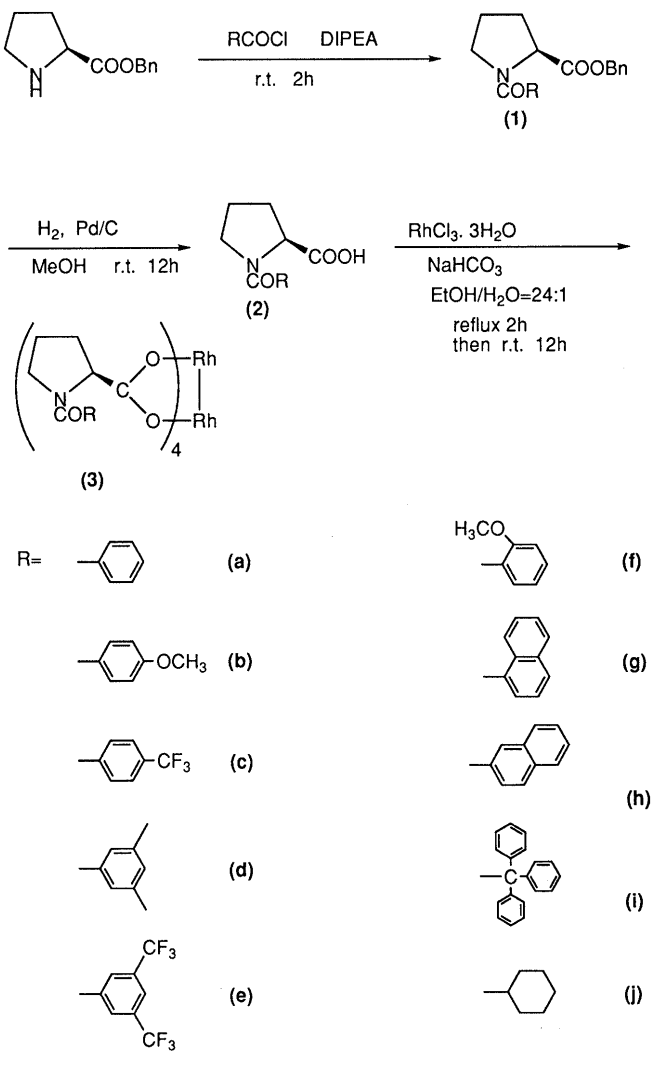

Chart 1. Preparation of Chiral Rhodium-Prolinate Catalyst

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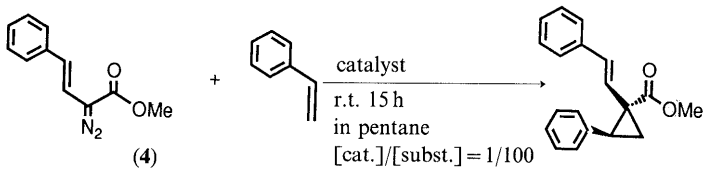
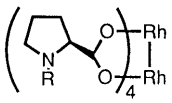
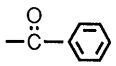
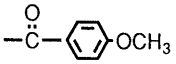
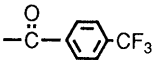
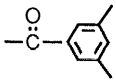
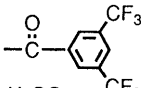
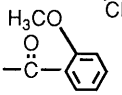
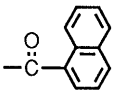
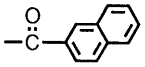
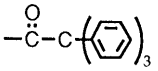
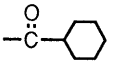
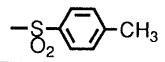
Table 1. Asymmetric Cyclopropanation of Styrene with Vinyldiazomethane (**4**) Catalyzed by Rh(II)–Chiral Prolinate



Catalyst		Yield (%)[a]	% ee	$[\alpha]_D^{20}$ (°)[b]	Configuration
3a		75	64	−100.9	1*S*,2*S*
3b		91	76	−111.9	1*S*,2*S*
3c		68	59	−92.49	1*S*,2*S*
3d		84	48	−75.86	1*S*,2*S*
3e		43	36	−56.50	1*S*,2*S*
3f		74	7	−11.36	1*S*,2*S*
3g		13	20	+31.73	1*R*,2*R*
3h		55	64	−100.8	1*S*,2*S*
3i		71	55	+86.87	1*R*,2*R*
3j		52	40	−62.55	1*S*,2*S*
		67	84	−132.5	1*S*,2*S*

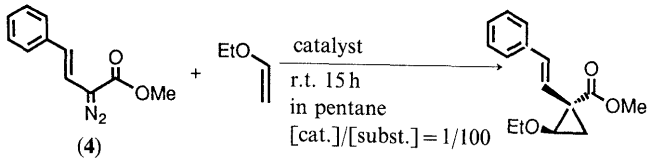
a) Determined by GC analysis. *b*) Calculated on the basis of the maximum rotation, $[\alpha]_D^{20}$ +157.1° (c = 1.1, $CHCl_3$), for the pure (*R*,*R*)-enantiomer.[4]

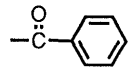
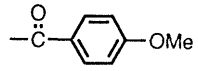
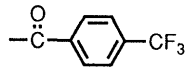
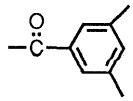
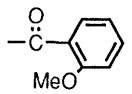
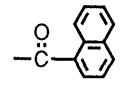
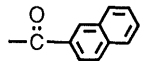
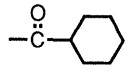
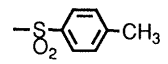
bulky substituent (**3g**) was a poor catalyst in respect to yield and enantioselectivity. Moreover, it is noteworthy that the directions of enantioselection in the products catalyzed by **3g** and **3i** were opposite to those catalyzed by the other complexes. Cyclopropanations of other olefins such as ethyl vinyl ether and 1-chloro-1-fluoroethylene, which differ from each other in the electronic factor, were carried out and the results are summarized in Tables 2 and 3.

Yields were determined as in the case of styrene. ^{1}H-NMR analysis suggested that only *E* cyclopropane was generated from ethyl vinyl ether, and that *E*/*Z* isomers were both generated from 1-chloro-1-fluoroethylene. The *E*/*Z* ratio was determined by ^{1}H-NMR and ^{1}H correlation spectroscopy (^{1}H-COSY) NMR analysis. The enantioselectivities in both cases were determined by ^{1}H-NMR analysis using chiral shift reagent, tris[3-(heptafluoropropylhydroxymethylene)-(+)-camphorato]praseodymium-(III) derivative [$Pr(hfc)_3$].

In the case of ethyl vinyl ether, the values of the yield and enantioselectivity were relatively similar, but the gap between the values of the yield and enantioselectivity of catalysts in the case of 1-chloro-1-fluoroethylene was much larger than that with styrene and ethyl vinyl ether. Thus, electron-rich catalysts such as **3b**, **3d**, and **3f** were greatly superior to electron-withdrawing catalysts in the case of the asymmetric cyclopropanation. Especially in the case of 1-chloro-1-fluoroethylene, **3b** and **3d** were more effective catalysts than rhodium(II)–chiral *N*-sulfonyl-substituted proline complex in terms of enantioselectivity, though less effective in terms of reactivity. Moreover, the direction of the enantioselection of the products catalyzed by **3i** was opposite to that of the other complexes. The reason why the direction of the enantioselection of the products was reversed between **3g** or **3i** and other catalysts may be steric hindrance, judging from several proposed mechanisms.[6]

Table 2. Asymmetric Cyclopropanation of Ethyl Vinyl Ether with Vinyldiazomethane (4) Catalyzed by Rh(II)–Chiral Prolinate



Catalyst		Yield (%)[a]	% ee[b]
3a		78	47
3b		78	52
3c		76	23
3d		70	60
3f		70	19
3g		70	14 (reverse)
3h		71	47
3j		69	19
		84	64

a) Determined by GC analysis. *b*) Determined by ^{1}H-NMR analysis using a chiral shift reagent, Pr(hfc)$_3$. Pr(hfc)$_3$ = Tris[3-(heptafluoropropylhydroxymethylene)-(+)-camphorato]praseodymium(III) derivative.

Further investigations are in progress in our laboratory.

In conclusion, asymmetric cyclopropanation of various olefins, which differ in steric and electronic factors, with vinyldiazomethane catalyzed by several rhodium(II)–prolinate complexes was carried out and it was found that the steric and electronic effects of the rhodium(II) complexes and substrates influenced the enantioselectivity and catalytic activity. The products of the asymmetric cyclopropanation are proposed to be key intermediates for new cyclopropane amino acid[7] that have been reported to have interesting biological activities.[8]

Experimental

General Procedures All melting points were determined with a micro-melting point apparatus (Yanagimoto) and are uncorrected. Optical rotations were measured on a JASCO DIP-140 digital polarimeter. Proton nuclear magnetic resonance (^{1}H-NMR) spectra were recorded on a JEOL JNM-GX270 spectrometer using tetramethylsilane (TMS) as an internal standard; the abbreviations of signal patterns are as follows: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; br, broad. Column chromatography was carried out on a silica gel (Kieselgel 60, 70—230 mesh, Merck).

(4*S*)-1-(Benzoyl)-L-proline Benzyl Ester (1a) A solution of *N*-ethyldiisopropylamine (2.6 ml, 15 mmol) in CH_2Cl_2 (10 ml) was added dropwise to a solution of L-proline benzyl ester hydrochloride (1.8 g, 7.0 mmol) and benzoyl chloride (1 g, 7.3 mmol) in CH_2Cl_2 (20 ml), under ice cooling. The reaction mixture was stirred overnight at room temperature, washed with H_2O (30 ml × 2) and saturated aqueous NaCl (30 ml), dried over $MgSO_4$, and then evaporated. The residue was chromatographed on silica gel with Et_2O to give **1a** (1.67 g, colorless oil). Yield 66%, $[\alpha]_D^{20}$ −75.8° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.60—2.40 (m, 4H, 2 × $-CCH_2C-$), 3.55—3.70 (m, 2H, $-NCH_2$), 4.70—4.79 (m, 1H, $-CH-$), 5.19—5.32 (m, 2H, $-CH_2-$), 7.30—7.45 (m, 10H, Ar-H).

(4*S*)-1-(4′-Methoxybenzoyl)-L-proline Benzyl Ester (1b) 4-Methoxybenzoyl chloride (1.37 g, 8.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1b** (2.33 g, colorless oil). Yield 84%, $[\alpha]_D^{20}$ −67.3° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.40 (m, 4H, 2 × $-CCH_2C-$), 3.55—3.80 (m, 2H, $-NCH_2$), 3.98 (s, 3H, $-OCH_3$), 4.67—4.80 (m, 1H, $-CH-$), 5.15—5.30 (m, 2H, $-CH_2-$), 6.83—6.95 (m, 2H, Ar-H), 7.35 (s, 5H, Ar-H), 7.53—7.63 (m, 2H, Ar-H).

(4*S*)-1-(4′-Trifluoromethylbenzoyl)-L-proline Benzyl Ester (1c) 4-Trifluoromethylbenzoyl chloride (1.68 g, 8.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1c** (2.6 g, colorless oil). Yield 85%, $[\alpha]_D^{20}$ −20.7° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.57—2.40 (m, 4H, 2 × $-CCH_2C-$), 3.40—3.65 (m, 2H, $-NCH_2$), 4.70—4.80 (m, 1H, $-CH-$), 5.17—5.30 (m, 2H, $-CH_2-$), 7.35 (s, 5H, Ar-H), 7.60—7.75 (m, 4H, Ar-H).

(4*S*)-1-(3′,5′-Dimethylbenzenecarbonyl)-L-proline Benzyl Ester (1d) 3,5-Dimethylbenzoyl chloride (1.7 g, 10.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1d** (4.0 g, colorless oil). Yield 95%, $[\alpha]_D^{20}$ −69.2° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.83—2.15 (m, 4H, 2 × $-CCH_2C-$), 2.34 (s, 6H, 2 × CH_3), 3.49—3.65 (2H, m, $-NCH_2$), 4.70—4.79 (m, 1H, $-CH-$), 5.15—5.29 (m, 2H, $-CH_2-$), 7.04 (s, 1H, Ar-H), 7.16 (s, 2H, Ar-H), 7.38 (s, 5H, C_6H_5-).

(4*S*)-1-[3′,5′-Bis(trifluoromethyl)benzoyl]-L-proline Benzyl Ester (1e) 3,5-bis(trifluoromethyl)benzoyl chloride (1.3 g, 5.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1e** (1.5 g, colorless oil). Yield 57%, $[\alpha]_D^{20}$ −66.4° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.93—2.20 (m, 4H, 2 × $-CCH_2C-$), 3.46—3.65 (m, 2H, $-NCH_2$), 4.07—4.19 (m, 1H, $-CH-$), 5.15—5.29 (m, 2H, $-CH_2-$), 7.38 (s, 5H, C_6H_5-), 7.80—8.02 (m, 3H, Ar-H).

(4*S*)-1-(2′-Methoxybenzenecarbonyl)-L-proline Benzyl Ester (1f) 2-Methoxybenzoyl chloride (1.37 g, 8.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1f** (2.5 g, colorless oil). Yield 91%, $[\alpha]_D^{20}$ −66.3° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.40 (m, 4H, 2 × $-CCH_2C-$), 3.35—3.55 (m, 2H, $-NCH_2$), 3.96 (s, 3H, $-CH_3$), 4.70—4.80 (m, 1H, $-CH-$), 5.15—5.30 (m, 2H, $-CH_2-$), 7.35 (s, 5H, Ar-H), 6.80—7.00, 7.30—7.41 (m, 4H, Ar-H).

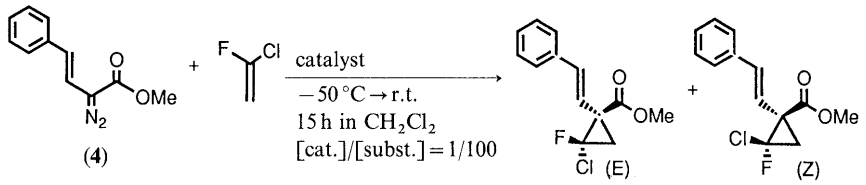
(4*S*)-1-(α-Naphthalenecarbonyl)-L-proline Benzyl Ester (1g) α-Naphthalenecarbonyl chloride (1.5 g, 8.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1g** (2.65 g, colorless oil). Yield 91%, $[\alpha]_D^{20}$ −71.0° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.43 (m, 4H, 2 × $-CCH_2C-$), 3.56—3.80 (m, 2H, $-NCH_2$), 4.76—4.81 (m, 1H, $-CH-$), 5.19—5.32 (m, 2H, $-CH_2-$), 7.38 (s, 5H, Ar-H), 7.50—7.92 (m, 7H, Ar-H).

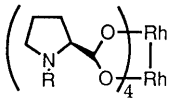
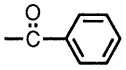
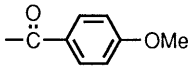
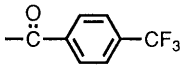
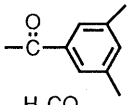
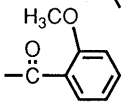
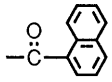
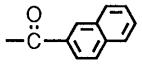
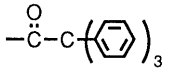
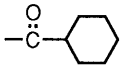
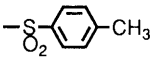
(4*S*)-1-(β-Naphthalenecarbonyl)-L-proline Benzyl Ester (1h) β-Naphthalenecarbonyl chloride (1.5 g, 8.0 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1h** (2.3 g, colorless oil). Yield 80%, $[\alpha]_D^{20}$ −51.2° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.43 (m, 4H, 2 × $-CCH_2C-$), 3.17—3.37 (m, 2H, $-NCH_2$), 4.84—4.89 (m, 1H, $-CH-$), 5.19—5.32 (m, 2H, $-CH_2-$), 7.45 (s, 5H, Ar-H), 7.30—8.09 (m, 7H, Ar-H).

(4*S*)-1-(Triphenylmethylcarbonyl)-L-proline Benzyl Ester (1i) Triphenylmethylcarbonyl chloride (1.8 g, 6.1 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1i** (2.3 g, colorless oil). Yield 67%, $[\alpha]_D^{20}$ −20.5° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.57—1.80 (m, 4H, 2 × $-CCH_2C-$), 2.51—2.69 (m, 2H, $-NH_2$), 4.60—4.70 (m, 1H, $-CH-$), 5.12—5.30 (m, 2H, $-CH_2-$), 7.20—7.42 (m, 15H, Ar-H).

(4*S*)-1-(Cyclohexanecarbonyl)-L-proline Benzyl Ester (1j) Cyclohexanecarbonyl chloride (1.5 g, 10 mmol) was subjected to the procedure used for the synthesis of **1a** to give **1j** (3.0 g, colorless oil). Yield 93%, $[\alpha]_D^{20}$ −72.4° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.18—2.42 (m,

Table 3. Asymmetric Cyclopropanation of 1-Chloro-1-fluoroethylene with Vinyldiazomethane (**4**) Catalyzed by Rh(II)–Chiral Prolinate



Catalyst		Yield (%)[a]	*E*:*Z*[b]	*E* ee[c]	*Z* ee[c]
3a		32	2:1	49	58
3b		63	7:3	69	71
3c		5	8:5	57	52
3d		38	2:1	71	80
3f		43	2:1	21	21
3g		8	1:1	—	—
3h		26	11:5	67	51
3i		7	2:1	33 (reverse)	33 (reverse)
3j		24	9:5	33	33
		80	8:5	56	56

a) Determined by GC analysis. *b*) Determined by ^{1}H-NMR analysis. *c*) Determined by ^{1}H-NMR analysis using the chiral shift reagent Pr(hfc)$_3$. Pr(hfc)$_3$ = Tris[3-heptafluoropropylhydroxymethylene)-(+)-camphorato]praseodymium(III) derivative.

15H, $-CH_2-$), 3.49—3.70 (m, 2H, $-NCH_2$), 4.56—4.70 (m, 1H, –CH–), 5.00—5.17 (m, 2H, $-CH_2-$), 7.35 (s, 5H, Ar-H).

(4*S*)-1-(Benzoyl)-L-proline (2a) A solution of **1a** (1.5 g, 4.1 mmol) in CH_3OH (30 ml) containing 5% Pd–C (0.15 g) was hydrogenated under 1 atm pressure. After stirring for 16 h at 20 °C the mixture was filtered through a pad of Celite and the filtrate was concentrated to dryness to give a white solid. This was crystallized from ether–ethanol to give **2a** (0.9 g, colorless crystals). Yield 72%, mp 120 °C, $[\alpha]_D^{20}$ −137° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.43 (m, 4H, 2 × $-CCH_2C-$), 3.52—3.60 (m, 2H, $-NCH_2$), 4.70—4.80 (m, 1H, –CH–), 7.40—7.50 (m, 5H, Ar-H). *Anal.* Calcd for $C_{12}H_{13}NO_3 \cdot 1/4H_2O$: C, 64.41; H, 6.08; N, 6.26. Found: C, 64.46; H, 6.17; N, 6.01.

(4*S*)-1-(4′-Methoxybenzoyl)-L-proline (2b) A solution of **1b** (1.5 g, 6.5 mmol) was hydrogenated as described for the synthesis of **2a** to give **2b** (1.2 g, colorless crystals). Yield 69%, mp 132 °C, $[\alpha]_D^{20}$ −120° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.84—2.35 (m, 4H, 2 × $-CCH_2C-$), 3.57—3.76 (m, 2H, $-NCH_2$), 3.89 (s, 3H, $-OCH_3$), 4.65—4.80 (m, 1H, –CH–), 6.80—6.97 (m, 2H, Ar-H), 7.57—7.68 (m, 2H, Ar-H). *Anal.* Calcd for $C_{13}H_{15}NO_4 \cdot 2/5H_2O$: C, 60.88; H, 6.20; N, 5.46. Found: C, 60.71; H, 6.08; N, 5.37.

(4*S*)-1-(4′-Trifluoromethylbenzoyl)-L-proline (2c) A solution of **1c** (2.6 g, 6.6 mmol) was hydrogenated as described for the synthesis of **2a** to give **2c** (1.7 g, colorless crystals). Yield 86%, mp 123 °C, $[\alpha]_D^{20}$ −93.3° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.40 (m, 4H, 2 × $-CCH_2C-$), 3.45—3.60 (m, 2H, $-NCH_2$), 4.70—4.80 (m, 1H, –CH–), 7.65—7.73 (m, 4H, Ar-H). *Anal.* Calcd for $C_{13}H_{12}NO_3F_3$: C, 54.36; H, 4.21; N, 4.88. Found: C, 54.45; H, 4.19; N, 4.90.

(4*S*)-1-(3′,5′-Dimethylbenzoyl)-L-proline (2d) A solution of **1d** (4.0 g, 11.3 mmol) was hydrogenated as described for the synthesis of **2a** to give **2d** (2.7 g, colorless crystals). Yield 91%, mp 123 °C, $[\alpha]_D^{20}$ −76.7° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.45 (m, 4H, 2 × $-CCH_2C-$), 2.34 (s, 6H, 2 × CH_3), 3.49—3.67 (m, 2H, $-NCH_2$), 4.70—4.79 (m, 1H, –CH–), 7.09 (s, 1H, Ar-H), 7.15 (s, 2H, Ar-H). *Anal.* Calcd for $C_{14}H_{17}NO_3 \cdot 1/8H_2O$: C, 67.38; H, 6.97; N, 5.61. Found: C, 67.45; H, 6.91; N, 5.52.

(4*S*)-1-(3′,5′-bis(trifluoromethyl)benzoyl)-L-proline (2e) A solution of **1e** (1 g, 2.2 mmol) was hydrogenated as described for the synthesis of **2a** to give **2e** (600 mg, colorless oil). Yield 73%, mp 133 °C, $[\alpha]_D^{20}$ −46.3° (c = 1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.90—2.25 (m, 4H, 2 × $-CCH_2C-$), 3.24—3.43 (m, 2H, $-NCH_2$), 4.05—4.23 (m, 1H, –CH–), 7.70—7.92 (m, 3H, Ar-H). *Anal.* Calcd for $C_{14}H_{11}NO_3F_6$: C, 47.33; H,

3.12; N, 3.94. Found: C, 47.59; H, 3.04; N, 3.88.

(4*S*)-1-(2′-Methoxybenzoyl)-L-proline (2f) A solution of **1f** (2.0 g, 5.6 mmol) was hydrogenated as described for the synthesis of **2a** to give **2f** (1.2 g, colorless crystals). Yield 71%, mp 123 °C, $[\alpha]_D^{20}$ −146° (c=1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.20 (m, 4H, 2×–CCH_2C–), 3.35—3.40 (m, 2H, –NCH_2), 4.02 (s, 3H, –CH_3), 4.80—4.85 (m, 1H, –CH–), 5.15—5.30 (m, 2H, –CH_2–), 6.75—6.95, 7.30—7.45 (m, 4H, Ar-H). *Anal.* Calcd for $C_{13}H_{15}NO_4 \cdot 1/3H_2O$: C, 61.17; H, 6.18; N, 5.49. Found: C, 61.10; H, 6.12; N, 5.40.

(4*S*)-1-(α-Naphthalenecarbonyl)-L-proline (2g) A solution of **1g** (2.5 g, 6.7 mmol) was hydrogenated as described for the synthesis of **2a** to give **2g** (1.7 g, colorless crystals). Yield 88%, mp 235 °C, $[\alpha]_D^{20}$ −27.4° (c=1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.23—2.43 (m, 4H, 2×–CCH_2C–), 3.20—3.40 (m, 2H, –NCH_2), 4.92—4.99 (m, 1H, –CH–), 7.40—7.97 (m, 7H, Ar-H). *Anal.* Calcd for $C_{16}H_{15}NO_3$: C, 71.36; H, 5.61; N, 5.20. Found: C, 71.17; H, 5.55; N, 5.12.

(4*S*)-1-(β-Naphthalenecarbonyl)-L-proline (2h) A solution of **1h** (1.5 g, 8.0 mmol) was hydrogenated as described for the synthesis of **2a** to give **2h** (2.3 g, colorless crystals). Yield 80%, mp 170 °C, $[\alpha]_D^{20}$ −112° (c=1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.43 (m, 4H, 2×–CCH_2C–), 3.17—3.37 (m, 2H, –NCH_2), 4.84—4.89 (m, 1H, –CH–), 7.30—8.09 (m, 7H, Ar-H). *Anal.* Calcd for $C_{16}H_{15}NO_3 \cdot 2/3H_2O$: C, 68.31; H, 5.85; N, 4.98. Found: C, 68.29; H, 6.00; N, 4.83.

(4*S*)-1-(Triphenylmethylcarbonyl)-L-proline (2i) A solution of **1i** (2.3 g, 4.7 mmol) was hydrogenated as described for the synthesis of **2a** to give **2i** (1.6 g, colorless crystals). Yield 85%, mp 185 °C, $[\alpha]_D^{20}$ −14.9° (c=1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.40—2.15 (m, 4H, 2×–CCH_2C–), 2.60—2.68 (m, 2H, –NH_2), 4.60—4.80 (m, 1H, –CH–), 7.30—7.60 (m, 15H, Ar-H). *Anal.* Calcd for $C_{25}H_{23}NO_3$: C, 77.90; H, 6.01; N, 3.63. Found: C, 78.21; H, 6.15; N, 3.99.

(4*S*)-1-(Cyclohexanecarbonyl)-L-proline (2j) A solution of **1j** (3.0 g, 9.0 mmol) was hydrogenated as described for the synthesis of **2a** to give **2j** (1.9 g, colorless crystals). Yield 87%, mp 96 °C, $[\alpha]_D^{20}$ −166° (c=1.0, $CHCl_3$). ^{1}H-NMR ($CDCl_3$) δ: 1.23—2.44 (m, 15H, –CH_2–), 3.57—3.70 (m, 2H, –NCH_2), 4.62—4.78 (m, 1H, –CH–), 7.50 (br, 1H, COOH). *Anal.* Calcd for $C_{12}H_{19}NO_3$: C, 63.98; H, 8.50; N, 6.22. Found: C, 63.82; H, 8.55; N, 6.08.

Dirhodium(II) Tetrakis[(4*S*)-1-(benzoyl)-L-prolinate] Complex (3a) $RhCl_3 \cdot 3H_2O$ (175 mg, 0.66 mmol) in 20 ml of EtOH–H_2O (95 : 5) was added dropwise to a solution of **2a** (900 mg, 3.3 mmol) and $NaHCO_3$ (270 mg, 3.2 mmol) in 80 ml of EtOH–H_2O (95 : 5). The reaction mixture was refluxed under an argon atmosphere for 2.5 h and held for 16 h at room temperature, then filtered and evaporated. The residue was taken up in saturated aqueous $NaHCO_3$ (30 ml) and extracted with CH_2Cl_2 (50 ml). The organic solution was washed with saturated aqueous NaCl (20 ml), dried over anhydrous Na_2SO_4, and evaporated. The product was chromatographed on silica gel with Et_2O–EtOH (9 : 1—4 : 1) as an eluent to give a blue-green solid. This was heated under vacuum at 70 °C to give **3a** (200 mg, green solid). Yield 56%. ^{1}H-NMR ($CDCl_3$) δ: 1.65—2.23 (m, 16H, 2×–CCH_2C–), 3.22—3.43 (m, 8H, –NCH_2), 4.56—4.70 (m, 4H, –CH–), 7.27—7.48 (m, 20H, Ar). *Anal.* Calcd for $C_{48}H_{48}N_4O_{12}Rh_2 \cdot 3H_2O$: C, 50.89; H, 4.81; N, 4.95. Found: C, 50.46; H, 4.71; N, 4.63.

Dirhodium(II) Tetrakis[(4*S*)-1-(4′-methoxybenzoyl)-L-prolinate] Complex (3b) **2b** (1.2 g, 4.0 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3b** (140 mg, green solid). Yield 25%. ^{1}H-NMR ($CDCl_3$) δ: 1.50—2.12 (m, 16H, 2×–CCH_2C–), 3.25—3.60 (m, 8H, –NCH_2), 3.78 (s, 12H, –OCH_3) 4.57—4.65 (m, 4H, –CH–), 6.75—7.53 (m, 16H, Ar-H). *Anal.* Calcd for $C_{52}H_{56}N_4O_{16}Rh_2 \cdot 2H_2O$: C, 50.58; H, 4.90; N, 4.54. Found: C, 50.55; H, 5.30; N, 4.81.

Dirhodium(II)Tetrakis[(4*S*)-1-(4′-trifluoromethylbenzoyl)-L-prolinate] Complex (3c) **2c** (1.6 g, 5.3 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3c** (190 mg, green solid). Yield 26%. ^{1}H-NMR ($CDCl_3$) δ: 1.60—2.21 (m, 16H, 2×–CCH_2C–), 3.35—3.54 (m, 8H, –NCH_2), 4.73—4.80 (m, 4H, –CH–), 7.44—7.63 (m, 16H, Ar-H), *Anal.* Calcd for $C_{52}H_{44}F_{12}N_4O_{12}Rh_2$: C, 46.23; H, 3.28; N, 4.15. Found: C, 46.21; H, 3.79; N, 3.77.

Dirhodium(II) Tetrakis[(4*S*)-1-(3′,5′-dimethylbenzoyl)-L-prolinate] Complex (3d) **2d** (1.5 g, 5.7 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3d** (150 mg, green solid). Yield 23%. ^{1}H-NMR ($CDCl_3$) δ: 2.05 (s, 24H, 2×CH_3), 1.67—2.35 (m, 16H, 2×–CCH_2C–), 3.27—3.45 (m, 8H, –NCH_2), 4.50—4.69 (m, 4H, –CH–), 6.91 (s, 4H, Ar-H), 7.03 (s, 8H, Ar-H). *Anal.* Calcd for $C_{56}H_{64}N_4O_{12}Rh_2 \cdot 1.5H_2O$: C, 55.27; H, 5.55; N, 4.60. Found: C, 55.25; H, 5.80; N, 4.38.

Dirhodium(II) Tetrakis[(4*S*)-1-[3′,5′-bis(trifluoromethyl)benzoyl]-L-prolinate] Complex (3e) **2e** (600 mg, 1.6 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3e** (100 mg, green solid). Yield 37%. ^{1}H-NMR ($CDCl_3$) δ: 1.75—2.07 (m, 16H, 2×–CH_2–), 3.04—3.27 (m, 8H, –NCH_2), 3.92—4.03 (m, 4H, –CH–), 7.50—7.68 (m, 12H, Ar-H). *Anal.* Calcd for $C_{56}H_{40}F_{24}N_4O_{12}Rh_2$: C, 41.45; H, 2.48; N, 3.45. Found: C, 41.66; H, 2.75; N, 3.23.

Dirhodium(II) Tetrakis[(4*S*)-1-(2′-methoxybenzonyl)-L-prolinate] Complex (3f) **2f** (1.2 g, 4.0 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3f** (120 mg, green solid). Yield 21%. ^{1}H-NMR ($CDCl_3$) δ: 1.40—2.12 (m, 16H, 2×–CH_2–), 3.05—3.32 (m, 8H, –NCH_2), 3.82 (s, 12H, –OCH_3), 4.56—4.70 (m, 4H, –CH–), 6.80—7.37 (m, 4H, Ar-H). *Anal.* Calcd for $C_{52}H_{56}N_4O_{16}Rh_2 \cdot 2H_2O$: C, 50.58; H, 4.90; N, 4.54. Found: C, 50.57; H, 5.18; N, 3.99.

Dirhodium(II) Tetrakis[(4*S*)-1-(α-naphthalenecarbonyl)-L-prolinate] Complex (3g) **2g** (1.5 g, 5.3 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3g** (240 mg, green solid). Yield 40%. ^{1}H-NMR ($CDCl_3$) δ: 1.23—2.04 (m, 16H, 2×–CH_2–), 3.07—3.34 (m, 8H, –NCH_2), 4.72—4.89 (m, 4H, –CH–), 7.28—7.97 (m, 28H, Ar-H). *Anal.* Calcd for $C_{64}H_{56}N_4O_{12}Rh_2 \cdot 2.6H_2O$: C, 57.98; H, 4.46; N, 4.22. Found: C, 57.95; H, 4.93; N, 4.03.

Dirhodium(II) Tetrakis[(4*S*)-1-(β-naphthalenecarbonyl)-L-prolinate] Complex (3h) **2h** (1.3 g, 4.6 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3h** (250 mg, green solid). Yield 42%. ^{1}H-NMR ($CDCl_3$) δ: 1.80—2.26 (m, 16H, 2×–CH_2–), 3.27—3.47 (m, 8H, –NCH_2), 4.67—4.75 (m, 4H, –CH–), 7.35—7.83 (m, 28H, Ar-H). *Anal.* Calcd for $C_{64}H_{56}N_4O_{12}Rh_2 \cdot 2.6H_2O$: C, 57.98; H, 4.46; N, 4.22. Found: C, 58.15; H, 4.76; N, 4.05.

Dirhodium(II) Tetrakis[(4*S*)-1-(triphenylmethylcarbonyl)-L-prolinate] Complex (3i) **2i** (1.3 g, 3.2 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3i** (200 mg, green solid). Yield 39%. ^{1}H-NMR ($CDCl_3$) δ: 0.80—2.15 (m, 16H, 2×–CH_2–), 2.00—2.42 (m, 8H, –NCH_2), 4.38—4.42 (m, 4H, –CH–), 7.05—7.20 (m, 60H, Ar-H). *Anal.* Calcd for $C_{100}H_{88}N_4O_{12}Rh_2 \cdot 3H_2O$: C, 66.81; H, 5.27; N, 3.12. Found: C, 66.84; H, 5.24; N, 3.06.

Dirhodium(II) Tetrakis[(4*S*)-1-(cyclohexanecarbonyl)-L-prolinate]-Complex (3j) **2j** (1.8 g, 7.5 mmol) was subjected to the procedure used for the synthesis of **3a** to give **3j** (250 mg, green solid). Yield 30%. ^{1}H-NMR ($CDCl_3$) δ: 1.18—2.02 (m, 60H, –CH_2–), 3.30—3.62 (m, 8H, –NCH_2), 4.21—4.38 (m, 4H, –CH–). *Anal.* Calcd for $C_{48}H_{72}N_4O_{12}Rh_2$: C, 51.43; H, 6.65; N, 4.87. Found: C, 51.42; H, 6.96; N, 4.18.

Asymmetric Cyclopropanation of Styrene with Methyl (*E*)-2-Diazo-4-phenyl-3-butenoate (4) Catalyzed by Rhodium(II) Prolinate A solution of methyl (*E*)-2-diazo-4-phenyl-3-butenoate (0.75 mmol) in dry CH_2Cl_2 (30 ml) was added dropwise to a stirred mixture of styrene (0.3 g, 3.2 mmol) and rhodium(II) prolinate (7.5×10^{-3} mmol) in dry *n*-pentane (10 ml) under an argon atmosphere. The reaction mixture was stirred for 16 h, then *cis*-decalin (28 mg) was added an internal standard for GC analysis to determine the yield. The mixture was evaporated and the residue was purified by silica gel preparative TLC to give a colorless oil. The ^{1}H-NMR analysis showed no indication of the formation of the *Z* isomer. The extent of asymmetric induction and the absolute configuration were determined by the procedure reported in reference 3. *Rf* 0.37 (Et_2O–*n*-hexane (1 : 5)). ^{1}H-NMR ($CDCl_3$) δ: 1.83 (1H, dd, J=7.4, 5.0 Hz), 2.05 (1H, dd, J=8.7, 6.0 Hz), 3.06 (1H, dd, J=9.0, 7.6 Hz), 3.78 (3H, s), 6.16 (1H, d, J=15.7 Hz), 6.39 (1H, d, J=15.7 Hz), 7.18—7.30 (10H, m).

Asymmetric Cyclopropanation of Ethyl Vinyl Ether with Methyl (*E*)-2-Diazo-4-phenyl-3-butenoate (4) Catalyzed by Rhodium(II) Prolinate A solution of methyl (*E*)-2-diazo-4-phenyl-3-butenoate (0.75 mmol) in dry CH_2Cl_2 (30 ml) was added dropwise to a stirred mixture of ethyl vinyl ether (0.54 g, 7.5 mmol) and rhodium(II) prolinate (7.5×10^{-3} mmol) in dry *n*-pentane (10 ml) under an argon atmosphere. The reaction mixture was stirred for 16 h, then *cis*-decalin (28 mg) was added as an internal standard for GC analysis to determine the yield. The mixture was evaporated and the residue was purified by silica gel preparative TLC to give a colorless oil. ^{1}H-NMR analysis showed no indication of the formation of the *Z* isomer. The extent of asymmetric induction and the absolute configuration were determined by the procedure reported in reference 3. *Rf* 0.40 (Et_2O–*n*-hexane (1 : 5)). FAB-MS: 247 $(M+H)^+$. ^{1}H-NMR ($CDCl_3$) δ: 1.11 (3H, t, J=7.0 Hz), 1.62 (1H, dd, J=6.0, 6.0 Hz), 1.86 (1H, dd, J=6.6, 6.6 Hz), 3.06 (2H, q, J=6.9 Hz), 3.73 (3H, s), 3.79 (1H, dd, J=5.0, 4.9 Hz), 6.44 (1H, d, J=16.2 Hz), 6.73 (1H, d, J=16.5 Hz), 7.18—7.40 (5H, m).

Asymmetric Cyclopropanation of 1-Chloro-1-fluoroethylene with Methyl (*E*)-2-Diazo-4-phenyl-3-butenoate (4) Catalyzed by Rhodium(II) Prolinate A solution of methyl (*E*)-2-diazo-4-phenyl-3-butenoate (0.75 mmol) in dry CH_2Cl_2 (30 ml) was added dropwise to a stirred mixture of 1-chloro-1-fluoroethylene (1.0 g, 12 mmol) and rhodium(II) prolinate (7.5×10^{-3} mmol) in dry CH_2Cl_2 (20 ml) under an argon atmosphere at $-50°C$. The reaction mixture was stirred for 16 h, then *cis*-decaline (28 mg) was added as an internal standard for GC analysis to determine the yield. The mixture was evaporated and the residue was purified by silica gel preparative TLC to give a colorless oil. ^{1}H-NMR and ^{1}H-COSY NMR analysis showed the *E*/*Z* ratio, and the extent of asymmetric induction was determined by ^{1}H-NMR analysis using the chiral shift reagent Pr(hfc)$_3$. *Rf* 0.27 (Et_2O–*n*-hexane (1 : 5)). FAB-MS: 255 $(M+H)^+$. ^{1}H-NMR ($CDCl_3$) δ: 1.83 (3H, dd, J=6.5, 6.3 Hz), 2.62 (1H, dd, J=8.0, 8.5 Hz), 3.79 (3H, s), 6.44 (1H, d, J=16.0 Hz), 6.60 (1H, d, J=16.3 Hz), 7.22—7.40 (5H, m).

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