Tetrahedron Vol. 49, No 47, pp 10793-10806, 1993
Printed in Great Britain

0040-4020/93 $6 00+.00

Highly Enantioselective Dihydroxylation of Olefins by Osmium Tetroxide with Chiral Diamines

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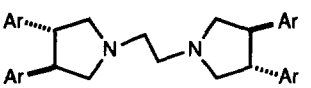
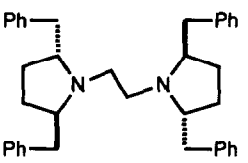
(*Received in Japan* 9 *August* 1993; *accepted* 13 *September* 1993)

Abstract. Enantioselective dihydroxylation of olefins by osmium tetroxide with chiral diamines was examined. The hydroxylation employing **1** gave exceptionally high optical yields in the production of diols from mono-, *trans*-di-, and trisubstituted olefins Virtually complete asymmetric induction was observed in the reaction of *trans*-β-methylstyrene The stereochemical outcome of the asymmetric reaction strongly suggested that the oxidation proceeded via organometallacycle **14**

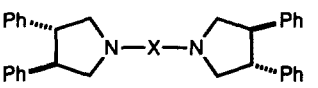
Osmium tetroxide oxidation is the most reliable method to form *cis*-vicinal diol from olefins.[1,2] It is widely used in the key steps of synthesis of biologically active natural products because of its reliability and generality. Asymmetric dihydroxylation is a versatile chemical transformation because it creates two contiguous asymmetric carbon in a single step. Since diols can be easily transformed into other functional groups,[3] this method provides a powerful tool for the synthesis of optically active natural products.[4] As tertiary amines are known to coordinate osmium tetroxide and to promote dihydroxylation of olefins, several successful methods have been developed by employing stoichiometric[5-13] or substoichiometric[14-17] amount of osmium tetroxide-chiral amine complexes. We have reported the design and synthesis of novel chiral diamines **1**, **2** and their application to the enantioselective 1,2-addition of Grignard reagents to aldehydes.[18] We describe herein the detail of the highly enantioselective dihydroxylation of olefins by osmium tetroxide with chiral diamines and the mechanistic studies of dihydroxylation of olefins with osmium tetroxide.[19]



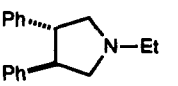
(-)-**1**: Ar = Ph
(-)-**2**: Ar = 3,5-Xylyl



(+)-**3**



(-)-**1**. X = CH_2CH_2
(-)-**4**. X = $CH_2CH_2CH_2$
(-)-**5**· X = 1,2-phenylene
(-)-**6**: X = 2,2'-biphenylene



(-)-**7**

Fig. 1. Chiral Amines for Asymmetric Dihydroxylation with OsO_4

Enantioselective Dihydroxylation of trans-Stilbene

In order to estimate the ability of asymmetric induction in osmium tetroxide oxidation with various types of chiral amines, asymmetric oxidation of *trans*-stilbene was examined with amines **1**-**7** in toluene at -78°C. Enantiomeric excess was determined by optical rotation of the diol. The results are summarized in Table 1. Although diamine with trimethylene spacer **4** gave a diol of poor enantioselectivity, diamine with ethylene spacer **1** gave a diol of excellent enantioselectivity (90 % ee). Diamines with 1,2-phenylene **5** and 2,2'-biphenylene **6** spacer , and diamine with substituents on 2,2',5,5'-position **3** did not promote the osmylation at all, which may be due to the weak coordination of aniline-type nitrogen to osmium. Monoamine **7**, a half component of diamine **1** exhibited an extremely slower reaction rate and poor asymmetric induction. To our surprise, diamine **2** gave a diol of opposite absolute configuration in good enantioselectivity, which will be discussed with the mechanism of this asymmetric reaction in later section of this paper.

Table 1. Enantioselective Oxidation of *trans*-Stilbene with Various Amines in Toluene at -78°C

Run	Ligand	$[\alpha]_D^{21}$(EtOH) (°)	ee (%)	Conf.	Yield (%)
1	none	-	-	-	0
2	(-)-**1**	-82.2	90	*SS*	86
3	(-)-**2**	+60.2	66	*RR*	62
4	(+)-**3**	-	-	-	0
5	(-)-**4**	-24.7	27	*SS*	62
6	(-)-**5**	-	-	-	0
7	(-)-**6**	-	-	-	0
8	(-)-**7**	-22.0	24	*SS*	5

Olefin/OsO_4/Diamine=1.0/1.1/1.2

Solvent effect was next examined with chiral diamine **1**. Among various solvent surveyed (Table 2), THF (Run 5) was found to be best for this asymmetric reaction. Poor yield in ether (Run 4) is probably due to the solubility of chiral diamine **1**. The reaction in DME (Run 3) gave black precipitate of low valent osmium species which had no more reactivity toward olefins.

Table 2. Enantioselective Oxidation of *trans*-Stilbene with (-)-**1** in Various Solvents at -78°C

Run	solvent	$[\alpha]_D^{21}$(EtOH)(°)	ee (%)	yield (%)
1	toluene	-82.2	90	86
2	CH_2Cl_2	-70.3	77	53
3	DME	-	-	0
4	ether	-86.5	95	16
5	THF	-85.7	94	77

Olefin/OsO_4/Diamine=1 0/1 1/1.2

Enantioselective Dihydroxylation of Olefins with Chiral Diamine 1

Employing the best reaction condition above, olefins with various patterns of substituents were oxidized by osmium tetroxide with chiral diamine **1** (Table 3) in THF at -78°C. Olefin was added to a bright wine-red solution of osmium tetroxide-**1** complex to afford corresponding osmate (VI) ester, which was reductively hydrolyzed to diol with lithium aluminum hydride (Run 1-7, 9-12) or sodium bisulfite (Run 8, 13, 14). The chiral diamine **1** was easily recovered as a HCl salt without any loss of its optical purity simply by filtration after adding aqueous HCl to the crude mixture. Among monosubstituted olefins (Run 1-3), styrene was oxidized in excellent ee (Run 1), but olefin with bulky substituent such as 3,3-dimethylbutene was oxidized slowly in poor ee. All the *trans*-disubstituted olefins examined were oxidized in excellent ee. Virtually complete asymmetric induction was observed in the reaction of *trans*-β-methylstyrene (Run 6). Olefins with *cis*- and *gem*-substituents did not give satisfactory optical yields. Trisubstituted olefins were oxidized in moderate to good ee. Cyclohexenones gave only 40-50 % ee, but 83 % ee was observed in the reaction of phenylcyclohexene. The asymmetric reaction with (+)-**1** gave the same degree of ee with opposite absolute configuration (Run 5). It is noteworthy that enantioselection in the present reaction is shown by the general presentation in Fig. 2 without exceptions. Since both (-)- and (+)-**1** are readily accessible in optically pure form, this method allows the synthesis of both enantiomers of diol with predictable absolute configuration from olefin.

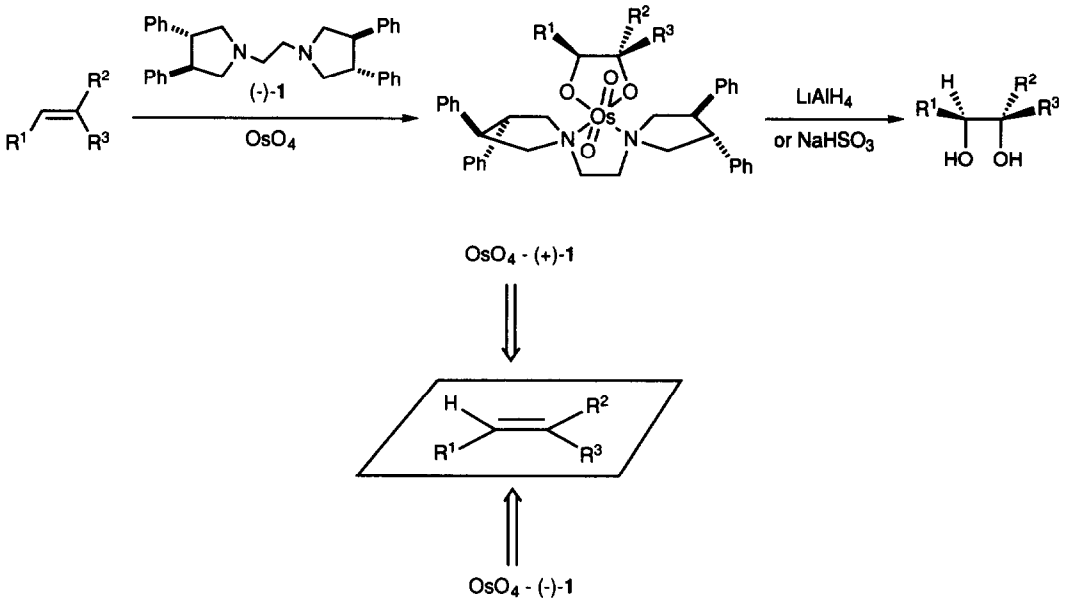
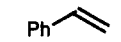
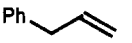
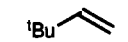
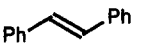
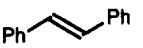
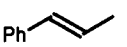
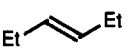
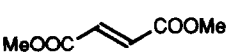
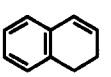
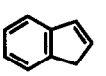
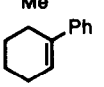
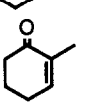
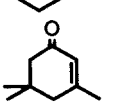


Fig 2. Enantioselective Dihydroxylation by OsO_4 with (+)- or (-)-**1**

Table 3. Enantioselective Dihydroxylation of Olefins with (-)-**1** in THF at -110°C

Run	Olefin[a]	$[\alpha]_D$(solvent) (°)	ee (%) (Conf)	Yield(%)
1		+57.3 ($CDCl_3$)	90 (*S*)	71
2		-17.0 (EtOH)	46 (*S*)	74
3[b]		+2.0 ($CHCl_3$)	8 (*S*)	73
4		-88.5 (EtOH)	97 (1*S*,2*S*)	85
5[c]		+87.4 (EtOH)	96 (1*R*,2*R*)	71
6		+31.1 (EtOH)	99 (1*S*,2*S*)[d]	73
7		-20.4 (H_2O)	90 (1*S*,2*S*)	80
8		+17.3 (H_2O)	93 (1*R*,2*R*)	67
9		-21.0 (MeOH)	29 (1*R*,2*S*)	24
10		+3.0 ($CHCl_3$)	6 (1*R*,2*S*)	70
11		+1.7 (EtOH)	30 (*S*)[d]	81
12		-16.1 (benzene)	83 (1*S*,2*S*)	83
13		-28.3 ($CHCl_3$)	41[e]	83
14		+14.2 ($CHCl_3$)	50	74

a) Olefin/OsO_4/Diamine=1.0/1.1/1.2 b) The reaction was performed at -78°C c) (+)-**1** was used instead of (-)-**1** d) Ee was determined by NMR analysis of the corresponding MTPA ester e) Ee was determined by NMR analysis with chiral shift reagent ($Eu(hfc)_3$ in $CDCl_3$)

Mechanism of Oxidation with Osmium Tetroxide

Proposed Mechanism of Dihydroxylation by Osmium Tetroxide

Two mechanisms have been proposed for the osmylation of alkenes. One is direct [3+2]-cycloaddition of both oxygens to the termini of double bond via a concerted five-membered cyclic transition state **10.** Hoffmann presented a result of molecular orbital calculations supporting this six-electron transition state.[20] The reactive species in amine accelerated conditions is supposed to be a 20-electron complex **9**. The rate acceleration by amines was explained by the distortion of the osmium tetroxide geometry to a more reactive form by amine coordination to osmium. A variation of this mechanism was proposed by Corey and his coworkers.[10, 21, 22] They favor the five-membered transition state model, but proposed that the alkene is attacked by one equatorial oxygen and one axial oxygen shown by **13** instead of **10.** They suggested that such a transition state is electronically favorable as well. The other mechanism, proposed by Sharpless and his coworkers,[23] involves [2+2]-cycloaddition of a C=C to a Os=O bond to form a four-membered metallacyclic intermediate **14**,[24] which subsequently undergoes rate-determining rearrangement to form osmate (VI) ester **11.** The rate acceleration by amines can be explained with the induction of Os-C bond cleavage by electron donation from amine. For the purpose of getting an evidence, spectroscopic studies were carried out to detect an osmium tetroxide-diamine complex **9** or an organometallic intermediate **14**, but no valuable information has been obtained.[25-29]

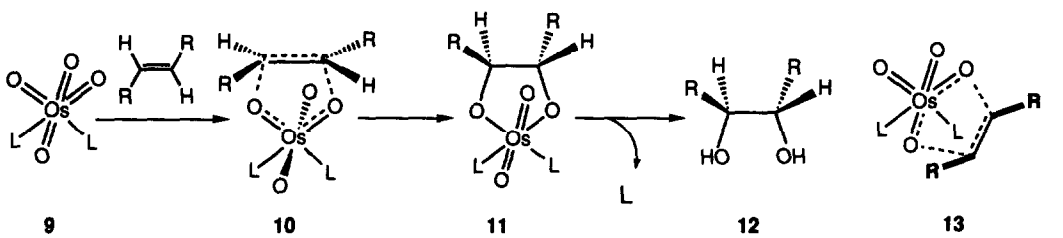


Fig. 3. [3+2]-Cycloaddition Mechanism

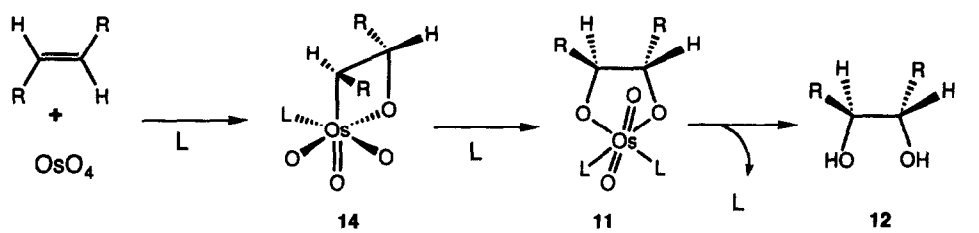


Fig. 4. [2+2]-Cycloaddition Mechanism

Structural Determination of Osmate (VI) ester-Diamine Complex

First of all we determined the structure of osmate (VI) ester-diamine complex. After treating *trans*-stilbene with osmium tetroxide in the presence of **1** under the same conditions as those of Table 3, the whole was concentrated and purified through silica gel chromatography (benzene-ether, 20/1) to afford **15** of mp 224°C (dec), $[\alpha]_D^{20}$-949° (c=0.102, $CHCl_3$) in 91 % yield. Structure was unambiguously determined to be **15** by X-ray

crystallography. Crystals were grown in a mixture of acetone-water solution as dark brown thin needles. Since the crystal was very small (about 0.02 x 0.1 x 0.2 mm in size), intensities were measured using graphite monochromate CuKα radiation and the absorption corrections were neglected. A total of 3870 reflections were measured within the 2θ range of 6° through 140°, of which 2998 were observed as above the 2σ (I) level. The crystal structure was determined by heavy atom method and refined by the block-diagonal-matrix least-squares calculations. The final R value was 0.057 allowing for the anisotropic thermal vibrations for all the heavier atoms. No hydrogen atom was included but dispersion corrections for C, O, N and Os atoms were accounted for assuming the absolute structure which yielded smaller R value as compared with the reversed structure. Figure 5 shows the structure of the complex drawn by ORTEP program. The atoms are shown as the ellipsoids of thermal vibrations each of which covers the region of finding the center of the corresponding atom with 30 % probability. As is seen in the figure, Os atom is coordinated by six atoms forming octahedral coordination group.

Crystal Data of **15**

empirical formula	$C_{48}H_{48}N_2O_4Os$
mol wt	907.1
cryst syst	orthorhombic
space group	$P2_12_12_1$
lattice param a (Å)	18.073 (10)
b (Å)	21.147 (11)
c (Å)	10.843 (7)
V (Å^3)	4144
Z	4
D_{cal} (g·cm^{-3})	1.454
μ for CuKα	61.4

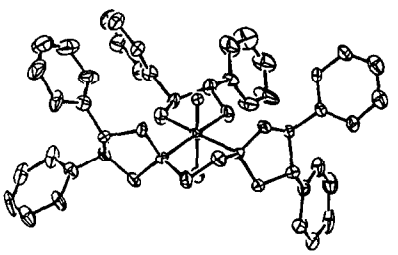


Fig. 5 ORTEP View of Osmate (VI) Ester-Diamine Complex **15**

Temperature Effect of Asymmetric Oxidation

Oxidation of *trans*-stilbene by osmium tetroxide with chiral amine **1** was examined at various temperatures (Table 4). As expected, the optical yield appeared to decrease by raising the reaction temperature. The color of the reagent, probably a complex of osmium tetroxide and **1**, changing gradually from bright wine-red to brown by increasing temperature and some decomposition occurred at temperature over -30°C. A nearly constant $\Delta\Delta G^{\neq}$, realizing in the temperature ranging from -110 to -48°C, implies the involvement of a single active species in the asymmetric oxidation.

Table 4. Enantioselective Oxidation of *trans*-Stilbene with (-)-**1** at Various Temperatures in THF

Run	Temp (°C)	Yield (%)	$[\alpha]_D^{21}$(EtOH)(°)	ee (%)	$\Delta\Delta G^{\neq}$(kcal/mol)
1	-110	85	-88.5	97	1.3
2	-78	77	-85.7	94	1.3
3	-48	74	-80.2	88	1.2
4	-23	67	-73.8	81	1.0
5	0	54	-45.3	50	0.6

Olefin/OsO_4/Diamine=1 0/1 1/1 2

Ligand Exchange Study of Osmate (VI) Ester

Treatment of four equivalent of racemic osmate-pyridine complex **16**, prepared from *trans*-stilbene by osmium tetroxide in pyridine with **1** gave a nearly 1:1 mixture of two diastereomeric complexes **17a** and **17b** in ^{1}H- and ^{13}C-NMR. Reductive hydrolysis of the mixture gave a diol of only 5 % ee. These results indicates that asymmetric oxidation is kinetically controlled by the stabilities of the diastereomeric transition states and is not a result of thermodynamic control governed by the stability of the resulting osmate ester-diamine complex.

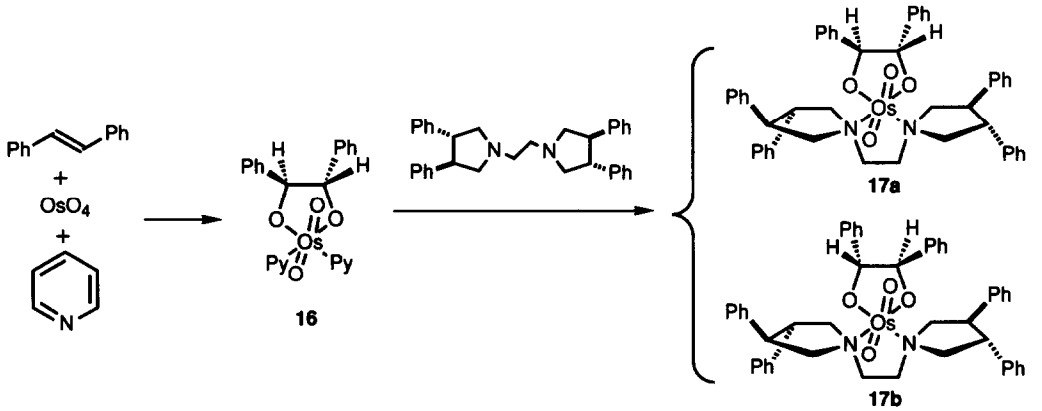


Fig. 6 Ligand Exchange Study of Osmate Ester

Hypothesis for Mechanism of Oxidation with Osmium Tetroxide

On the basis of these findings describe above, we would like to propose a stereochemistry of the present asymmetric oxidation. A [3+2]-cycloaddition pathway (a six-electron transition state) via a osmium tetroxide-ligand complex **18** explains the rate acceleration by diamine **1** and slower rate by monoamine. Assuming this mechanism, two structures of transition state can be supposed in our asymmetric oxidation because of high symmetry of the chiral diamine and the olefin. As **19b** would suffer from big steric interference between phenyl groups of diamine and stilbene, preferable transition state would be **19a**, which leads to (*R*,*R*)-diol of wrong enantiomer.[30]

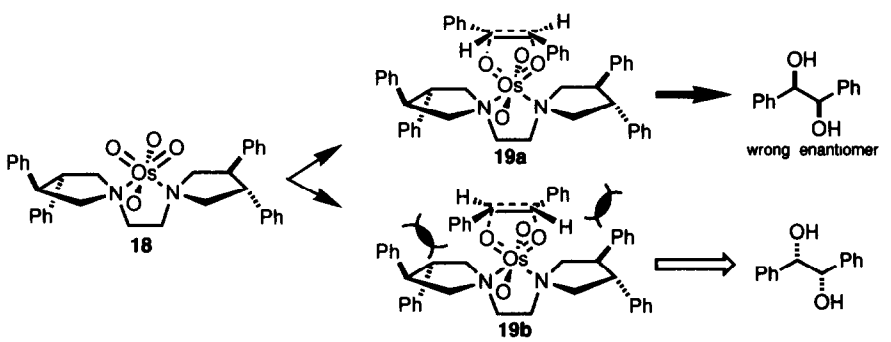


Fig 7 Stereochemical Outcome of [3+2]-Cycloaddition Mechanism

On the other hands, the alternative pathway via organometallacycles **20a** seems to explain the stereochemical outcome of the asymmetric reaction. In this case, four structures for intermediate can be supposed. Intermolecular attack by the second bulky monoamine **7** would be very slow. Intramolecular attack of nitrogen in the second pyrrolidine moiety of **20a** places the substituents in the least sterically demanding region, affording the osmate ester **15** in accord with the observed enantioface differentiation. On the other hand, severe steric interactions between phenyl groups on the coordinated pyrrolidine part and on the four membered metallacycle would retard the formation of the osmate ester. Assuming the reversible formation of the metallacycles from osmium tetroxide and olefin in the presence of ligand, the intermediacy of **20a** would be the best explanation for the present extremely efficient enantioface selection exhibited by the C_2-symmetric chiral diamine.

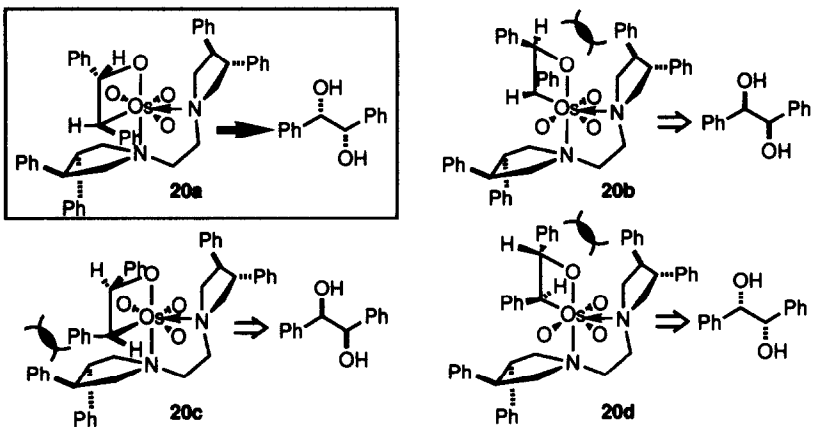
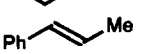
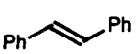


Fig. 8. Stereochemical Outcome by [2+2]-Cycloaddition Mechanism

Table 5. Enantioselective Dihydroxylation of Olefins with (-)-**2** in Toluene

Run	Olefin	$[\alpha]_D$(solvent) (°)	ee (%) (Conf)	Yield(%)	ee using (-)-**1** (%) (Conf)
1		-17.0 (EtOH)	46 (*S*)	72	47 (*S*)
2		-2.8 (benzene)	14 (1*S*,2*S*)	66	60 (1*S*,2*S*)
3		+3.4 (EtOH)	11 (1*S*,2*S*)	57	90 (1*S*,2*S*)
4		-39.4 ($CDCl_3$)	62 (*R*)	94	71 (*S*)
5		+60.2 (EtOH)	66 (1*R*,2*R*)	62	95 (1*S*,2*S*)

Olefin/OsO_4/Diamine=1.0/1 1/1.2

Dramatic Enantioselectivity Change with slight structural modification of diamine

In order to clarify the mechanism, oxidation with diamine **2** was examined intensively. As shown in Table 1, diamine **2** which has 3,5-xylyl group in place of phenyl group of **1** showed interesting behavior. The results of oxidation of other olefins are summarized in Table 5. Except only one case (Run 1), enantioselectivities decreased from 60 to 14 % and 90 to 11 %. Furthermore as shown in Runs 4 and 5, a sense of enantioselectivity dramatically changed in oxidations of styrene and stilbene to afford (*R*)- and (*RR*)-diols in 62 and 66 % ee, respectively. At the outset of our study we expected that modification of phenyl group of **1** to more bulky xylyl group would provide much more efficient enantioselectivity on the basis of steric ground. However, a ligand **2** caused to decreased enantioselectivity and even more change a sense of enantioface selection.

These unexpected observations may be rationalized only by the probable mechanistic pathway discussed above. In oxidation of *trans*-olefins and styrene with use of **1** (Run 2-5), the osmate ester corresponding to (*SS*)-diol would be formed through the structure similiar to **21a** rather than **21b**, **21c**, **21d**. With use of **2**, **21a** would suffer from steric interferences between methyl group of xylyl and R^1 group and reaction may turn to proceed to some extent through **21b**, giving diols with much more contribution of (*RR*)-diols. In oxidation of allylbenzene with **1** or **2** (Run 1), the reaction proceeds through the structure **21a** where steric repulsion between phenyl or xylyl group and R^1 can be avoided by rotating benzyl group (R^1) away from those groups. Though Corey's mechanism[10] might explain the stereochemical outcome of the asymmetric reaction using diamine **1**, it does not help the understanding for this asymmetric induction using diamine **2**. These results strongly support that oxidation proceeded via four-membered organometallacycle.

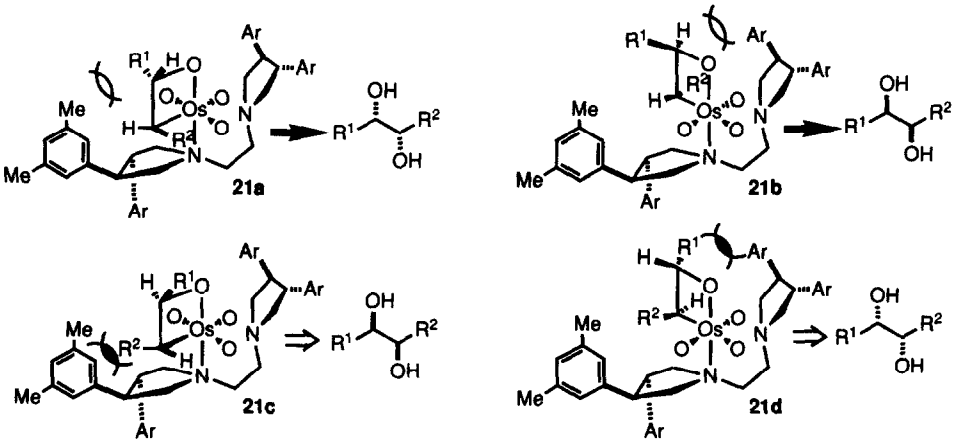


Fig. 9 Stereochemical Outcome by [2+2]-Cycloaddition Mechanism using **2**

Summary

Extremely high enantioface selection was achieved in *cis*-dihydroxylation of olefins with osmium tetroxide using diamine **1** as a chiral ligand. Since (+)- and (-)-**1** are readily accesible in optically pue forms, this method allows the synthesis of both enantiomers of diols with predictable absolute configuration. The stereochemical outcome strongly suggested that oxidation proceeded via four-membered organometallacyclic intermediate.

Experimental Section

Melting points were measured using a Büchi 510 melting point apparatus and are not corrected. Optical rotations were taken with a JASCO DIP-370 digital polarimeter. IR spectra were taken with a JASCO IRA-1 infrared spectrometer and expressed in cm^{-1}. ^1H-NMR spectra were taken in $CDCl_3$ with a JEOL GX-400 at 400 MHz, or a Hitachi R-24B spectrometer at 60 MHz. ^{13}C-NMR spectra were taken in $CDCl_3$ with a JEOL GX-400 at 100 MHz. Chemical shift values are expressed in ppm relative to internal tetramethylsilane. Abbreviations are as follows: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet, br, broad. MS spectra were taken with a JEOL DX-300 mass spectrometer. The products of asymmetric reaction were identified by NMR, IR, MS and their optical purities were determined by optical rotation otherwise noticed.

The maximum optical rotations used here for diols are as follows; 1-Phenylethane-1,2-diol[31] {$[\alpha]_D^{26}$-63.7° (c=5.45, $CDCl_3$) for *R*}; 3-Phenylpropane-1,2-diol[32] {$[\alpha]_D^{20}$-36° (c=1, EtOH) for *S*}; 3,3-Dimethylbutane-1,2-diol[33] {$[\alpha]_D^{25}$-28.1° (c=0.69, $CHCl_3$) for *R*}; 1,2-Diphenylethane-1,2-diol[34] {$[\alpha]_D^{21}$+91.0° (c=1.1, EtOH) for 1*R*,2*R*}; 1-Phenylpropane-1,2-diol[35] {$[\alpha]_D^{20}$+24.65° (c=1.91, EtOH) for 1*S*,2*S*}; Hexane-3,4-diol[36] {$[\alpha]_D^{25}$+22.7° (c=2.5, H_2O) for 1*R*,2*R*}; Dimethyl Tartarate[37] {$[\alpha]_D^{20}$+18.65° (c=2.49, H_2O) for 1*R*,2*R*}; 1,2,3,4-Tetrahydronaphthalene-1,2-diol[38] {$[\alpha]_D^{25}$-15.0° (c=2.43, MeOH) for 1*R*,2*S*}; Indan-1,2-diol[39] {$[\alpha]_D^{25}$-51.0° (c=0.40, $CHCl_3$) for 1*S*,2*R*}; 2-Phenylpropane-1,2-diol[40] {$[\alpha]_D^{8}$+5.4° (c=8.9, EtOH) for *S*}; 1-Phenylcyclohexane-1,2-diol[41] {$[\alpha]_D^{25}$-19.4° (c=1.23, benzene) for 1*S*,2*S*}; 2,3-Dihydroxy-2-methylcyclohexan-1-one[42] {$[\alpha]_D^{25}$+0.7° (c=1.01, $CHCl_3$) and ($[\alpha]_D^{25}$-0.8° (c=1.06, $CHCl_3$)}; 2,3-Dihydroxy-3,5,5-trimethylcyclohexan-1-one[42] {$[\alpha]_D^{25}$+28.6° (c=1.05, $CHCl_3$) and ($[\alpha]_D^{25}$-29.3° (c=1.09, $CHCl_3$)}.

Asymmetric dihydroxylation of trans-stilbene by osmium tetroxide with chiral diamine in toluene (Table 1, Run 2)

To a cooled (-78°C) solution of the chiral diamine (-)-**1** (0.32 g, 0.78 mmol) in toluene (10 ml) was added a solution of osmium tetroxide (0.16 g, 0.63 mmol) in toluene (2 ml). A solution of *trans*-stilbene (0.10 g, 0.57 mmol)) in toluene (1 ml) was added to the bright wine-red solution above and the whole was stirred for 6 h at -78°C. Lithium aluminum hydride (0.15 g, 3.9 mmol) and ether (10 ml) was added to the reaction mixture and the whole was stirred for 12 h at room temperature. Water (0.15 ml), 15 % NaOH (0.15 ml), water (0.45 ml) was added and the resulting precipitate was filtered off. The filtrate was concentrated and purified by silica gel column chromatography (dichloromethane-ether, 20/1) to afford diphenylethanediol (0.10 g, 86 %). $[\alpha]_D^{21}$-82.2° (c=1.00, EtOH), 90 % ee {lit.[34] $[\alpha]_D^{21}$+91.0° (c=1.1, EtOH)}. IR (Nujol): 3400, 1450. ^1H-NMR (60M, $CDCl_3$) δ: 2.90 (2H, brs, OH), 4.70 (2H, s, CH), 7.2-7.5 (10H, m, Ph). MS m/z: 214 (M^+).

Asymmetric dihydroxylation of trans-β-methylstyrene by osmium tetroxide with chiral diamine in THF (Table 3, Run 6)

To a cooled (-78°C) solution of the chiral diamine (-)-**1** (0.18 g, 0.38 mmol) in THF (10 ml) was added a solution of osmium tetroxide (88 mg, 0.35 mmol) in THF (2 ml). A solution of *trans*-β-methylstyrene (38 mg, 0.32 mmol)) in THF (1 ml) was added to the bright wine-red solution above and the whole was stirred for 6 h at -110°C. Lithium aluminum hydride (0.10 g, 2.6 mmol) was added to the reaction mixture and the whole was stirred for 12 h at room temperature. Water (0.10 ml), 15 % NaOH (0.10 ml), water (0.30 ml) was added and

the resulting precipitate was filtered off. The filtrate was concentrated and dissolved in ether (10 ml). 10 % HCl was added and the resulting precipitate of **1**·HCl was filtered, washed with water and ether, dried, and converted with NaOH back to unaltered (-)-**1** (0.45 g, 90 %). The water layer of original filtrate was extracted with ether (10 ml x2) and the combined organic layer was washed successively with brine, and dried over $MgSO_4$. Purification by silica gel column chromatography (hexane-ethyl acetate, 3/1) and following bulb to bulb distillation afforded (*S,S*)-phenylpropanediol (36 mg, 73 %) , $[\alpha]_D^{20}$+31.1° (c=1.79, EtOH). IR ($CHCl_3$): 3400, 1450. ^{1}H-NMR (60M, $CDCl_3$) δ: 1.05 (3H, d, *J*=7Hz, CH3), 3.10 (2H, brs, OH), 3.8-4.1 (1H, m, CH), 4.45 (1H, d, *J*=8Hz, CH), 7.30 (5H, s, Ph). MS m/z: 156 (M^+). The diol was converted into MTPA ester with (+)-MTPA-Cl in pyridine in quantitative yield. ^{1}H-NMR (400M, $CDCl_3$) δ: 1.24 (3H, d, *J*=8.0Hz, CH_3), 3.38 (3H, s, OCH_3), 3.42 (3H, s, OCH_3), 5.4-5.5 (1H, m, CH), 6.04 (isomer: 5.98) (1H, d, *J*=6.2Hz, CH), 7.1-7.4 (5H, m, Ph). The ratio of the integration showed the optical purity of the original diol was 99 % ee.

Asymmetric dihydroxylation of dimethyl fumarate by osmium tetroxide with chiral diamine in THF (Table3, Run 8)

To a cooled (-78°C) solution of the chiral diamine (-)-**1** (320 mg, 0.68 mmol) in THF (10 ml) was added a solution of osmium tetroxide (160 mg, 0.63 mmol) in THF (2 ml) A solution of dimethyl fumarate (80 mg, 0.56 mmol) in THF (2 ml) was added to the bright wine-red solution above at -110°C and the whole was stirred for 6 h at the same temperature. Sodium bisulfite (1.0 g), methanol (10 ml), and water (1 ml) was added to the reaction mixture and the whole was stirred for 14 h under reflux. The reaction mixture was basified with $NaHCO_3$ and concentrated. The residue was suspended in ethyl acetate (50 ml) and filtered through Celite pad. After concentration, ether (10 ml) and 10 % HCl (3 ml) was added to the residue and the mixture was stirred for 1 h at room temperature. The resulting precipitate of **1**·HCl was filtered, washed with water and ether, dried, and converted with NaOH back to unaltered (-)-**1** (0.30 g, 94 %). The filtrate was concentrated and purified by silica gel column chromatography (dichloromethane-ethyl acetate, 4/1) followed by bulb to bulb distillation afforded dimethyl tartarate (66 mg, 67 %) as a viscous oil of $[\alpha]_D^{20}$+17.3° (c=2.47, water), 93 % ee {lit.[37] $[\alpha]_D^{20}$+18.65° (c=2.49, H_2O)}. IR (Neat): 3400, 1750. ^{1}H-NMR (60M, $CDCl_3$) δ: 3.73 (2H, s, OH), 3.88 (6H, s, OCH_3), 4.59 (2H, s CH). MS m/z: 179 (MH^+).

Synthesis of Osmate (VI) - chiral diamine complex ***15***

A solution of osmium tetroxide (78 mg, 0.31 mmol) in THF (1 ml) was added to a solution of (-)-**1** (150 mg, 0.32 mmol) in THF (3 ml) at -78°C and stirred for 30 min. A solution of stilbene (55 mg, 0.31 mmol) in THF (1 ml) was added to the resulting red solution and the mixture was stirred for 30 min. Concentration and following silica gel column chromatography (benzene-ether, 20/1) and recrystallization (benzene-hexane) gave **15** (251 mg, 91 %) as a brown needles of mp 224° (dec). $[\alpha]_D^{20}$-949° (c=0.102, $CHCl_3$). IR (KBr): 1600, 1490, 1450, 1000, 840, 700. ^{1}H-NMR (400M, $CDCl_3$) δ: 3.11 (2H, dd, *J*=10, 11Hz), 3.5-3.7 (8H, m), 4.31 (2H, ddd, *J*=6, 10, 11Hz), 4.56 (2H, dd, *J*=10, 12Hz), 4.65 (2H, dd, *J*=6, 10Hz), 5.29 (2H, s), 7.0-7.5 (30H, m Ar). ^{13}C-NMR (100M, $CDCl_3$) δ· 49.60 (d), 50.65 (d), 66.58 (t), 69.15 (t), 99.13 (d), 126.77 (d), 126.86 (d), 127.24 (d), 127.42 (d), 127.59 (d), 128.12 (d), 128.38 (d), 128.47 (d), 138.95 (s), 139.94 (s), 141.34 (s). *Anal.* calcd for $C_{48}H_{48}N_2O_4Os$: C, 63.56; H, 5.33; N, 3.09. Found: C, 63.50; H, 5.31; N, 3.09. Further recrystallization from acetone-water gave thin needles for X-ray analysis.

Ligand exchange study of osmate (VI) ester

A solution of chiral diamine **1** (0.10 g, 0.21 mmol) in dichloromethane (6 ml) was added to a solution of osmate **16** (0.50 g, 0.84 mmol) in dichloromethane (50 ml) and the whole was stirred for 2 h at room temperature. The reaction mixture was concentrated and purified by silica gel column chromatography (benzene-ether, 20/1) to afford mixture of diastereomers of osmate **17a** and **17b** as brown needles of mp 215-225°C (dec). ^{1}H-NMR (400M, $CDCl_3$) δ: 5.29 (s), 5.30 (s). ^{13}C-NMR (100M, $CDCl_3$) δ: 49.49 (d), 49.60 (d), 50.50 (d), 50.62 (d), 66.18 (t), 66.58 (t), 68.10 (t), 68.28 (t), 68.57 (t), 69.15 (t), 98.58 (d), 99.13 (d). Ratios of integrations of each pairs of signals are all 1:1. Above osmate (140 mg) was reductively hydrolyzed with lithium aluminum hydride to afford diphenylethanediol (27 mg, 82 %). $[\alpha]_D^{21}$-4.4° (c=1.35, EtOH), 5 % ee.

Asymmetric dihydroxylation of trans-stilbene by osmium tetroxide with chiral diamine in toluene (Table 5, Run 5)

To a cooled (-78°C) solution of the chiral diamine (-)-**2** (0.16 g, 0.27 mmol) in toluene (10 ml) was added a solution of osmium tetroxide (64 mg, 0.25 mmol) in toluene (2 ml). A solution of *trans*-stilbene (41 mg, 0.23 mmol)) in toluene (1 ml) was added to the bright wine-red solution above and the whole was stirred for 6 h at -110°C. Lithium aluminum hydride (0.10 g, 2.6 mmol) and ether (20 ml) was added to the reaction mixture and the whole was stirred for 12 h at room temperature. Water (0.10 ml), 15 % NaOH (0.10 ml), water (0.30 ml) was added and the resulting precipitate was filtered off. The filtrate was concentrated and dissolved in ether (10 ml). 10 % HCl was added and the resulting precipitate of **2**·HCl was filtered, washed with water and ether, dried, and converted with NaOH back to unaltered (-)-**2** (0.14 g, 88 %). The water layer of original filtrate was extracted with ether (10 ml x2) and the combined organic layer was washed successively with brine, and dried over $MgSO_4$. Purification by silica gel column chromatography (benzene-ethyl acetate, 8/1) afforded (*S,S*)-diphenylethanediol (25.5 mg, 62 %) , $[\alpha]_D^{21}$+60.2° (c=1.01, EtOH), 66 % ee {lit.[34] $[\alpha]_D^{21}$+91.0° (c=1.1, EtOH)}.

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