Chiral sulfonated phosphines. Rhodium(I) -catalyzed asymmetric hydrogenolysis of epoxides [1]

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Abstract

Rhodium(I) complexes of sulfonated (−)-(2S,4S)-2,4-bis(diphenylphosphino)pentane ((S,S)-(BDPP)) are effective as catalyst for asymmetric hydrogenolysis of sodium *cis*-epoxysuccinate to sodium hydroxysuccinate in aqueous–organic two phase solvent system or in aqueous solution. It has been shown by deuterium labelling studies that both hydrogen and water participate in the aqueous hydrogenolysis as reactants and the reaction proceeds via the direct C–O bond cleavage of the epoxy group. High pressure NMR studies show the presence of rhodaoxetane–BDPP complexes as catalytic intermediates, which are formed by the oxidative addition of the epoxide to unsaturated Rh(I) species. Accordingly, a reaction mechanism has been proposed for the aqueous catalytic process. The use of a racemic substrate, sodium *trans*-phenylglycidate with the aqueous Rh-sulfonated (S,S)-BDPP system results in the kinetic resolution of the (2S,3R)-epoxide enantiomer. Thus, asymmetric aqueous catalytic hydrogenolysis could be a useful synthetic approach not only to chiral α-hydroxycarboxylic acid derivatives but also to chiral *trans*-substituted epoxides.

Keywords: Asymmetric hydrogenolysis; Epoxides; Rhodium complexes; Sulfonated (S,S)-BDPP complexes

1. Introduction

Water soluble organometallic compounds have attracted considerable interest as catalysts [1,2]. Recently a great deal of work has appeared on the synthesis of water soluble ligands by introducing highly polar functional groups such as sulphonate [3–7], carboxylic [8,9], hydroxide [10–12], quaternized and protonated amino groups [13–15] into monotertiary or ditertiary phosphines. Transition-metal complexes containing these phosphines have been applied to hydrogenation [6,7], hydroformylation [2], carbonylation [16], hydrocyanation [17], alkylation [18] and nucleophilic substitution

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reactions [19]. The development of water soluble catalysts is mainly due to the simplification of the catalyst-product separation and to the economy, safety and other advantages of using water as solvent [1].
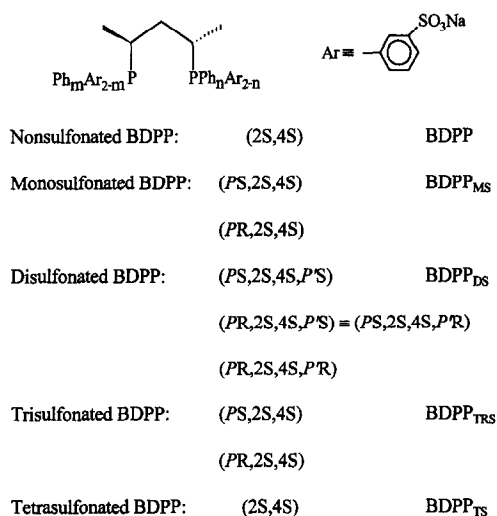
Recently we reported that rhodium(I) catalysts formed with sulfonated diphosphines are efficient for the asymmetric hydrogenation of enamides (88% ee) [7] and Schiff-bases (96% ee, maximum value) [20] in aqueous–organic two-phase solvent systems. In the latter case, catalysts containing sulfonated (S,S)-BDPP ligands gave higher enantioselectivity than the analogous lipophilic catalyst in a single organic solvent.

The first example of homogeneous catalytic asymmetric hydrogenolysis of an epoxide was reported only recently [21]. A number of most commonly used lipophilic (bisphosphine)rhodium(I) catalysts were tested by using cis-epoxysuccinic acid derivatives as substrates. The obtained malic acid products, which can also be prepared in several ways from tartate, are versatile building blocks for natural product synthesis. It was pointed out that the most suitable substrates for the reaction, such as the sodium salt, are not soluble in common organic solvents. Therefore, the reaction was accomplished in a solvent mixture of H_2O–MeOH (ca. 1:2–1:3). However, the solubility of the hydrophilic substrate was found to be rather limited (ca. 40 g/l) even in this polar solvent mixture. Thus, the use of a water soluble catalyst system in an aqueous or a two-phase catalytic approach seemed to be particularly suited for this reaction. For this reason, we have utilized rhodium(I) complexes containing sulfonated (S,S)-BDPP ligands as catalysts. Beside the catalytic results, we also report here on a study which has been carried out in order to elucidate the hydrogenolysis mechanism.

2. Results and discussion

2.1. Hydrogenolysis of sodium-cis-epoxysuccinate

Rh complexes containing monosulfonated (S,S)-BDPP, $BDPP_{MS}$ (Scheme 1), are very active and selective catalysts in ethylacetate–water two-phase solvent systems for the asymmetric hydrogenation

Nonsulfonated BDPP:	(2S,4S)	BDPP
Monosulfonated BDPP:	(PS,2S,4S)	$BDPP_{MS}$
	(PR,2S,4S)	
Disulfonated BDPP:	(PS,2S,4S,P'S)	$BDPP_{DS}$
	(PR,2S,4S,P'S) = (PS,2S,4S,P'R)	
	(PR,2S,4S,P'R)	
Trisulfonated BDPP:	(PS,2S,4S)	$BDPP_{TRS}$
	(PR,2S,4S)	
Tetrasulfonated BDPP:	(2S,4S)	$BDPP_{TS}$

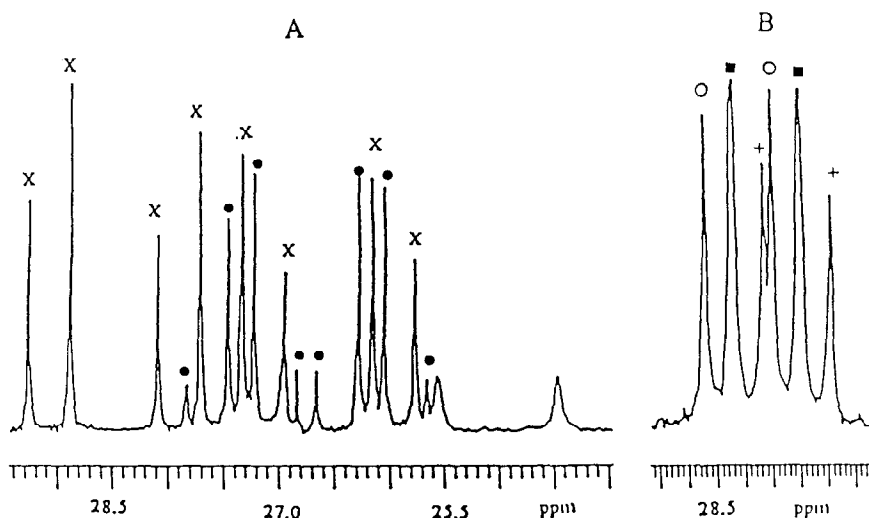Scheme 1. Sulfonated (S,S)-BDPP derivatives.

Fig. 1. ^{31}P–NMR spectra of the rhodium–cyclooctadiene complexes of BDPP$_{MS}$ (A) and BDPP$_{DS}$ (B).

of imines, whereas similar complexes containing the di- and higher sulfonated derivatives of the same ligand give only low hydrogenation activity and enantioselectivity [20]. The same phenomena were observed by Lensink and de Vries, who separated BDPP$_{MS}$ and BDPP$_{DS}$ by column chromatography and used these for the same catalytic reaction [22]. As a possible explanation for the difference, it has been assumed that the catalyst containing BDPP$_{MS}$, which is soluble in EtOAc, operates in the organic phase, while the hydrophilic BDPP$_{DS}$ or higher sulfonated derivatives remain in the aqueous phase [20,22].

We have found a facile alternative method for the separation of mono and disulfonated phosphines in the form of their rhodium complexes. When a mixture of BDPP$_{MS}$ and BDPP$_{DS}$ is reacted with [Rh(COD)Cl]$_2$ by using a P/Rh ratio of 2.2/1 in a two-phase solvent composition of H$_2$O–EtOAc, complexes with BDPP$_{MS}$ and BDPP$_{DS}$ dissolve exclusively in the organic and the aqueous phase, respectively. As shown in Fig. 1, the rhodium complex [Rh(COD)(BDPP$_{MS}$)]$^+$ of monosulfonated ligand is a 1:1 mixture of two diastereomers due to the chirality on the phosphorus, the rhodium complex [Rh(COD)(BDPP$_{DS}$)]$^+$ of the disulfonated ligand gives a 1:2:1 mixture of diastereomers due to the chirality of both phosphorus atoms. This easy separation allowed us to evaluate the catalytic behaviour of mono and disulfonated BDPP in epoxide hydrogenolysis.

The results of the aqueous and two-phase asymmetric hydrogenolysis of sodium *cis*-epoxysuccinate (Eq. (1)) by using rhodium complexes containing the sulfonated ligands under hydrogen pressure are summarized in Table 1.
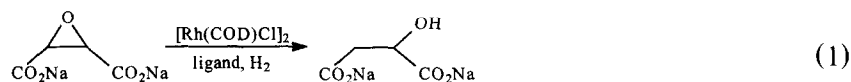
In contrast to the experience in imine hydrogenation above, the sulfonation degree of the ligand has only a relatively small effect on the enantioselectivity of the hydrogenolysis reaction. The highest ee (40%) has been achieved by the use of non-sulfonated BDPP and the enantioselectivity slightly

Table 1
Hydrogenolysis of sodium cis-epoxysuccinate [a]

| Entry	Ligand	Solvent	P_{H_2} (bar)	ee [b] (%)
1	BDPP	H_2O/MeOH	70	39 (41)
2	$BDPP_{MS}$	H_2O/EtOAc	100	36 (34)
3	$BDPP_{MS}$	H_2O/EtOAc	70	34
4	$BDPP_{MS}$	H_2O/EtOAc	35	34
5	$BDPP_{DS}$	H_2O	100	30
6	$BDPP_{DS}$	H_2O	70	32
7	$BDPP_{DS}$	H_2O/EtOAc	70	31
8	$BDPP_{TS}$	H_2O	70	26
9	$BDPP_{TS}$	H_2O	35	27

[a] Rh: P: substrate (1/2.2/100); 20°C, 6 h; Chemical yield > 90%.
[b] Determined by chiral GLC and by 400 MHz ^{1}H-NMR spectrum (in parentheses) of diastereomeric esters of (R)-(+)-α-methoxy-α-(trifluoromethyl)phenylacetic acid.

decreases by increasing the number of sulphonate groups on the ligand (Table 1). Apparently, unlike the hydrogenation of hydrophobic imines, the hydrogenolysis of a hydrophilic epoxide derivative is insensitive to the presence of an organic phase as far as water and a soluble catalyst are present. Thus, the use of an organic phase with the sulfonated derivatives seems to be redundant. As can be seen in Table 1, the enantioselectivity of the hydrogenolysis is also quite indifferent for the pressure of hydrogen.

2.2. Deuterium exchange experiments

In order to gain insight into the features of the aqueous catalytic reaction, deuterium labelling study was carried out. For this purpose, sodium cis-epoxysuccinate was reacted in deuterium oxide at 25°C under 20 bar of deuterium by using [Rh(COD)Cl]$_2$ and BDPP$_{TS}$ as in situ formed catalyst (Scheme 2). After methylation with diazomethane, the dimethyl ester of the product was analyzed by ^{1}H-NMR, which shows deuterium incorporation exclusively into the methylene (β-carbon) and hydroxy groups. The doublet of triplet at δ 2.88 ppm ($^2J_{H-H} = 4.1$ Hz, $^2J_{H-D} = 2.1$ Hz) corresponds to a β-H, whereas a doublet corresponding to the –C < group of the labelled ester appears at δ 4.51 ppm ($^2J_{H-H} = 4.1$ Hz). The other diastereotopic proton of the –CH$_2$– is missing owing to the replacement by deuterium. The unlabelled 2-hydroxy–succinic acid dimethyl ester gives two doublets of doublet at δ 2.80 ppm ($^2J = 16.5$ Hz and $^3J = 6.1$ Hz) and δ 2.88 ppm ($^2J = 16.5$ Hz and $^3J = 4.1$ Hz) corresponding to the diastereotopic protons of –CH$_2$– and a doublet of doublet at δ 4.51 ppm ($^3J = 6.1$ and 4.1 Hz) corresponding to the –CH < group. The ^{13}C{^{1}H}-NMR spectrum of the sodium salt in D$_2$O shows a singlet at δ 73.0 ppm for the –CH < group and a triplet at δ 45.0 ppm ($^3J_{C-D} = 20$ Hz) for the –CHD < group.
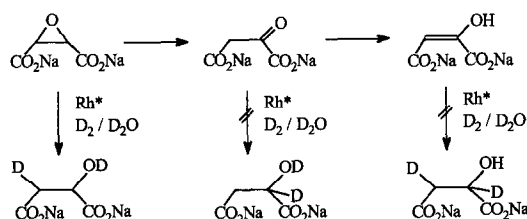
Scheme 2. An outline for the possible pathways in the hydrogenolysis of sodium cis-epoxysuccinate.

These results indicate that the incorporation of deuterium occurs highly regioselectively at the β-position and is only due to the dominant hydrogenolysis route. These spectral evidences unambiguously show that hydrogenolysis occurs and the reaction proceeds via a direct C–O bond cleavage, instead of an epoxide to ketone isomerization, followed by ketone or enol hydrogenation as shown in Scheme 2. The same phenomena were observed by Chan and Coleman by using lipophilic (bisphosphine)rhodium(I) catalyst systems [21].

By performing the reaction under hydrogen in D_2O or under deuterium in H_2O, almost quantitative deuterium or hydrogen incorporation, respectively, was observed into the β-position. This would indicate that hydrogen or deuterium, respectively, did not participate in the hydrogenolysis reaction. However, this is obviously not the case as the catalytic reaction does not proceed without the presence of these gases (not even by using an in situ formed catalytically active diaquae complex instead of diene precursors). A possible explanation for such deuterium incorporation could be a H/D exchange reaction between deuterium oxide and hydrogen (or water and deuterium) in the presence of a rhodium complex leading to the formation of HD. This reaction is well precedented in the literature [23]. However, the fact, that the extent of deuterium incorporation (by using $BDPP_{TS}$) into the β-position of the product is significantly higher than what can be expected from a theoretical isotopic composition in the aqueous and gas phases by assuming a complete H/D exchange (for example 86% deuterium incorporation at 70% theoretical deuterium content), indicates that the β-deuterium or hydrogen arises from the solvent D_2O or H_2O, respectively. This has also a significance for the proposed mechanism of catalytic hydrogenolysis (Scheme 3, vide infra). The proton of the hydroxyl group (or deuterium of the deuteroxyl group) of the product, which probably originates from the gas, hydrogen (or deuterium) gives exchange with D_2O (or H_2O) readily.

2.3. NMR studies on the hydrogenolysis mechanism

In order to further elucidate the reaction mechanism, NMR studies, including high pressure NMR measurements, were carried out. When a mixture of $BDPP_{MS}$ and $BDPP_{DS}$ is reacted with $[Rh(COD)Cl]_2$ by using a P/Rh ratio of 2.2/1 in a two-phase solvent composition of D_2O–EtOAc, the formation of several complexes is observed. ^{31}P-NMR spectroscopic analysis of both phases shows the exclusive participation of the rhodium complexes containing $BDPP_{MS}$ in the EtOAc phase, while the complexes containing $BDPP_{DS}$ remain in the aqueous phase. The two phase separation above can be an alternative method for the separation of mono- and disulfonated phosphines in the form of their respective rhodium complexes [22].

As shown in Fig. 1, $BDPP_{MS}$ yields two different diene complexes in an equal amount. Each complex gives rise to an eight line pattern due to non-equivalence of the phosphorus atoms (see Chart 1) (in CD_2Cl_2: δ 28.5 ppm, dd, $^1J_{Rh-P} = 143$ Hz, δ 26.5 ppm, dd, $^1J_{Rh-P} = 141$ Hz, $^2J_{P-P} = 46$ Hz; δ 27.0 ppm, dd, $^1J_{Rh-P} = 143$ Hz, δ 26.4 ppm, dd, $^1J_{Rh-P} = 143$ Hz, $^2J_{P-P} = 46$ Hz). Due to the used slight excess of the ligand, a small amount of $Rh(BDPP_{MS})_2Cl$ is also formed (δ 25.0 ppm, d, $^1J_{Rh-P} = 134$ Hz).

The $[Rh(COD)Cl]_2$ dimer gives three different diene complexes in a 1:2:1 ratio (Fig. 1) in reaction with 2.2 eq. of $BDPP_{DS}$ (P/Rh = 2.2) (in D_2O: δ 27.1 ppm, d, $^1J_{Rh-P} = 142$ Hz, δ 27.6 ppm, d, $^1J_{Rh-P} = 142$ Hz, $^2J_{P-P} \approx 0$ Hz; δ 28.1 ppm, d, $^1J_{Rh-P} = 144$ Hz, which are also due to the different configurations of the phosphorus atoms in the isomers, i.e. R,R; R,S = S,R; S,S).

When $[Rh(COD)Cl]_2$ is treated with (S,S)-$BDPP_{TS}$ for 10 min in a D_2O/EtOAc two-phase solvent system at room temperature, the ^{31}P-NMR spectrum of the aqueous phase shows only a doublet at δ 29.3 ppm ($^1J_{Rh-P} = 144$ Hz) corresponding to the formation of $[Rh(COD)(S,S)-BDPP_{TS}]^+$. Due to
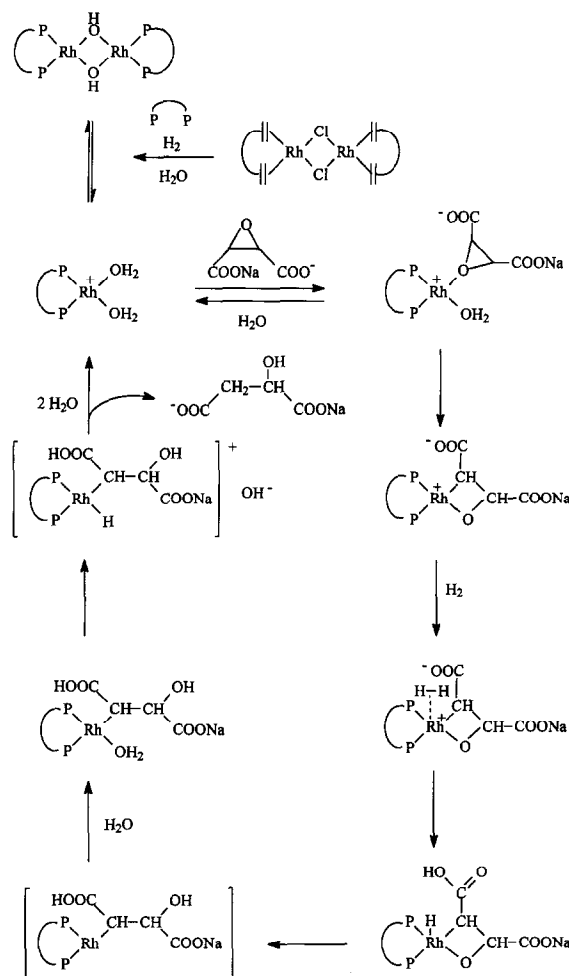
Scheme 3. Proposed catalytic cycle for aqueous hydrogenolysis of sodium cis-epoxysuccinate.

the simplicity of the NMR spectra of the latter derivative as compared to the mono- and disulfonated derivatives above, BDPP$_{TS}$ was used in further studies on the hydrogenolysis mechanism.

By pressurizing the aqueous solution of [Rh(COD)(S,S)–BDPP$_{TS}$]$^+$ to 30 bar with hydrogen in a high pressure NMR tube at room temperature, the stoichiometric formation of the catalytically active diaquae complex, [Rh(S,S)–BDPP$_{TS}$(D$_2$O)$_2$]$^+$ (δ 53.2 ppm, d, $^1J_{Rh-P}$ = 185 Hz) takes about 40 min. The diene and the latter solvent complex have been previously described [7]. The formation of a dihydride complex could not be detected even after keeping the tube under pressure for several days. The addition of another eq. amount of (S,S)–BDPP$_{TS}$ to the diaquae complex after releasing pressure or the initial mixing of 4 eq. with [Rh(COD)Cl]$_2$ resulted in the formation of the inactive [Rh–{(S,S)-BDPP$_{TS}$}$_2$]$^+$ complex (δ 24.9 ppm, d, $^1J_{Rh-P}$ = 131 Hz).

The diaquae complex gives four new isomeric complexes in a catalytic or stoichiometric reaction with the substrate sodium cis-epoxysuccinate in the presence or absence of hydrogen. The four isomers give rise to a doublet of doublets for each phosphorus atoms resulting in a thirty-two line ^{31}P-NMR spectrum (P$_1$ δ 35–40 ppm, P$_2$ 40–44 ppm, $^1J_{Rh-P}$ = 126, 136 Hz; 129, 131 Hz; 126, 130 Hz; 120, 139 Hz; $^2J_{P-P}$ = 42 Hz). This range of coupling constants are indicative for the presence of
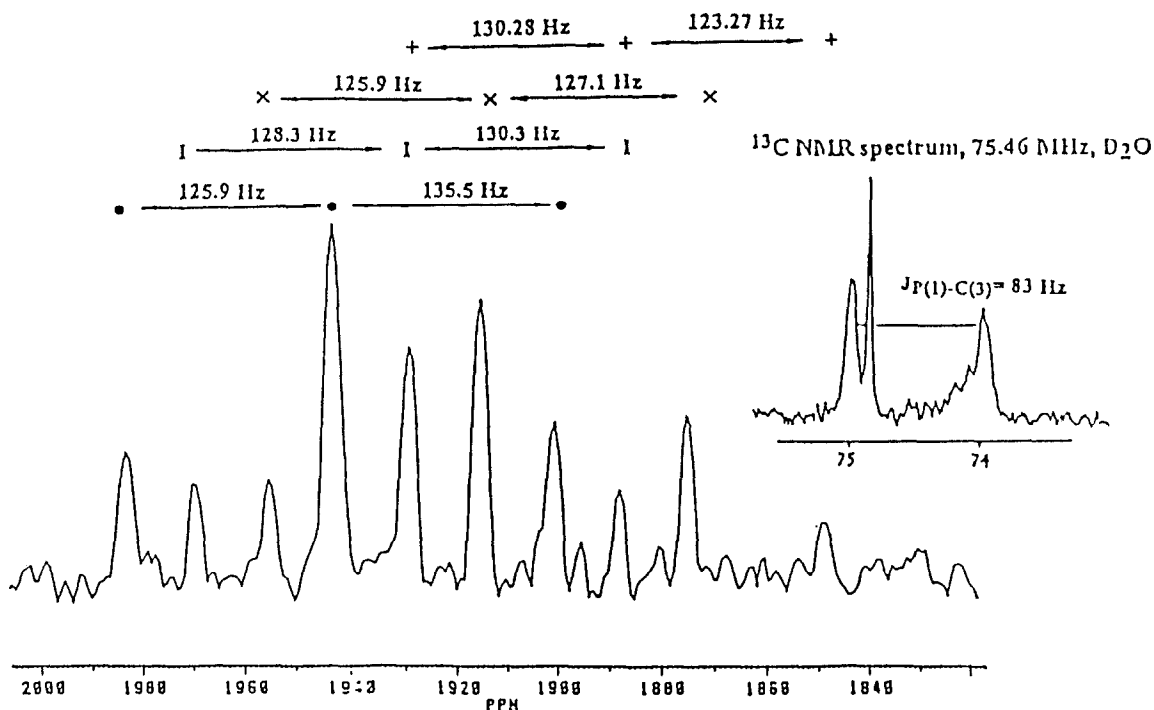
Fig. 2. [103]Rh–NMR (3.16 MHz, D_2O) and ^{13}C–NMR (75.46 MHz) spectra of rhodaoxetane complexes.

five coordinate Rh-diphosphine complexes [24]. Although, definitive assignments of the corresponding chemical shift values and coupling constants are not yet possible owning to the complexity of the ^{31}P-NMR spectra, the ^{31}P detected [103]Rh-NMR [25] spectrum, which is illustrated in Fig. 2 (δ 1944, 1929, 1916, 1887 ppm), is consistent with the premise that four isomers of a rhodaoxetane complex (Scheme 4) are present. The four isomers arise due to the presence of two chiral centres both in the ligand and the rhodaoxetane ring (Scheme 4).

The rhodaoxetane complexes containing (S,S)-BDPP$_{TS}$, which are shown in Scheme 4, have been assigned by their ^{1}H- and ^{13}C-NMR spectra. For example, the ^{13}C-NMR spectrum exhibits a large *trans* ^{13}C–P coupling (δ 76.2 ppm, doublet of multiplets, $J_{C-P} = 83$ Hz) for the carbon atom connected to rhodium. From the relatively small J_{Rh-P} coupling constants above, it is likely that the rhodaoxetane isomers are five-coordinate pyramidal complexes with a carboxy group being coordi-
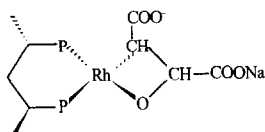
Four diastereomers: 2S, 3S, S, S

2S, 3R, S, S

2R, 3S, S, S

2R, 3R, S, S

Scheme 4. Proposed rhodaoxetane intermediates.

nated in the apical position. Metallaoxetanes, analogous to our intermediate, are often postulated as intermediates in various metal-mediated reactions of epoxides, in olefin metathesis, and in conversion of carbonyls to alkenes by metal alkylidenes [26].
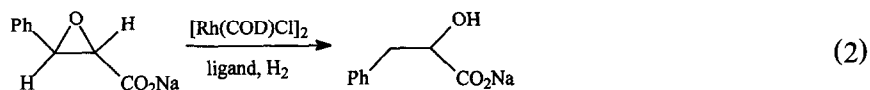
The proposed hydrogenolysis mechanism outlined in Scheme 3 implies that the first step is the formation of a substrate complex through the lone pair of the oxygen of the oxirane ring. Apparently, a very narrow reactivity window exists for this reaction. Epoxides without carboxy functionality are not hydrogenolyzed under similar conditions. The presence of a carboxylate anion probably helps to bring the substrate to the catalyst centre via the coordination of the oxygen of the oxirane ring. Our studies indicate that the oxidative addition of the C–O to the rhodium is a more facile process than the hydride formation. Rhodium hydrides are not readily produced from rhodium(I) complexes containing one eq. of diphosphines such as diop and dppe [27,28].

The rate determining reaction of the hydrogenolysis, as judged by the observation of rhodaoxetane complexes in catalytic reaction mixtures, is the reaction of rhodaoxetane with hydrogen, which involves the heterolytic splitting of H_2 and the formation of hydrido rhodium(III) complexes (Scheme 3). The heterolytic splitting of hydrogen is assumed to be the consequence of the parallel effects of the positively charged central metal ion (Rh(III)) and the carboxylate anion. The Rh(III) can be considered as a weak acid and the carboxylate anion is a relatively strong base. This may be regarded as the driving force for the heterolytic bond-breaking of hydrogen.

The hydrogen transfer could lead to rhodium alkyl intermediates (assuming this takes place in the direction shown in Scheme 3). The oxidative addition of H_2O (or D_2O) could give hydridoalkyl-rhodium complexes. The second hydride transfer could then give the product and the diaquae catalyst complex. By using the Rh dimer in the presence of $BDPP_{TS}$, the formation of a small amount of possible binuclear μ-hydroxo rhodium complex, $[Rh(\mu\text{-}OH)(BDPP_{TS})]_2$ (δ 46.4 ppm, $^1J_{Rh-P} = 181.9$ Hz) has also been observed in catalytic experiments under hydrogen pressure. A similar binuclear μ-hydroxo rhodium complex, $[Rh(\mu\text{-}OH)(TPPTS)_2]_2$ has been suggested by Herrmann et al. in the reaction of $RhCl(TPPTS)_3$ with hydrazine [29].

2.4. Kinetic resolution of racemic trans-phenylglycidate

The results obtained in the hydrogenolysis of sodium cis-epoxysuccinate prompted us to examine the bond cleavage by using a racemic substrate. One would expect such an asymmetric catalytic system to be sensitive to pre-existing chirality in the substrate. Indeed, by the use of racemic sodium trans-phenylglycidate instead of a prochiral cis-epoxysuccinate derivative as substrate (Eq. (2)), kinetic resolution of one of the epoxide enantiomers has been observed. As shown in Eq. (2), the C–O bond cleavage of the unsymmetrically substituted substrate proceeds regioselectively in the β-position to the ester group. The hydrogenolysis results, which were obtained with the Rh–(S,S)-$BDPP_{TS}$ catalyst system, are summarized in Table 2.

$$\text{Ph} \overset{O}{\underset{H}{\diagup\diagdown}} \overset{H}{\underset{CO_2Na}{\diagdown\diagup}} \xrightarrow[\text{ligand, } H_2]{[Rh(COD)Cl]_2} \text{Ph} \diagup\diagdown \overset{OH}{\underset{CO_2Na}{\diagdown}} \tag{2}$$

As can be seen, the optical yield of the hydrogenolysis product depends on the conversion. Furthermore, the catalyst containing (S,S)-$BDPP_{TS}$ ligand favours the hydrogenolysis of the (2R,3S)-epoxide enantiomer resulting in a prevalence of the 2R-product enantiomer.

Table 2
Asymmetric hydrogenolysis of racemic sodium *trans*-phenylglycidate [a]

Conversion (%)	ee [b] (%)	k_R / k_S
15.7	23.0	1.66
38.4	18.4	1.61
48.4	16.2	1.58
63.1	15.0	1.68
83.8	10.0	1.81
96.1	2.1	1.40

[a] Reaction conditions: 20°C, 70 bar H_2, H_2O/EtOAc; Substrate/Rh/P = 100/1/2.2. Ligand: $BDPP_{TS}$.
[b] Determined by chiral GLC analysis of methyl-2-hydroxy-3-phenylpropionate.

Table 3
Kinetic resolution of *trans*-phenylglycidate [a]

| Ligand	Reaction time (h)	Conversion (%)	ee [b] (%)	k_R / k_S
$BDPP_{MS}$ [c]	6	70	28	1.6
$BDPP_{DS}$	0.5	58	25	1.8
$BDPP_{TS}$	0.5	29	11	1.9

[a] Reaction conditions: 20°C, 70 bar H_2, H_2O; Substrate/Rh/P = 100/1/2.2.
[b] ee of the remaining substrate was determined by chiral solvating agent (CSA: (S)-1-phenylethylamine).
[c] Solvent: H_2O/EtOAc. Ligand: $BDPP_{TS}$.

By knowing any two of the following three variables: the ee in the product, the conversion and the relative rate (k_{fast}/k_{slow}), the third one can be calculated [30]. Thus, the determination of optical purities of the hydrogenolysis product at given conversions allowed us to calculate relative rates (k_R/k_S), which are also included in Table 2. As can be seen, the k_R/k_S relative rate is not a function of the conversion, which indicates that the hydrogenolysis proceeds via kinetic resolution of the racemic substrate (Scheme 5).

Several instances the optical purity of the remaining (2S,3R)-epoxide enantiomer has also been determined (Table 3). For this purpose, the unreacted substrate was converted into the acid form at low temperature and analyzed by ^{1}H-NMR in the presence of (S)-phenylethylamine chiral solvating agent. For example, at 29% hydrogenolysis conversion above, 11% ee was determined in the substrate.
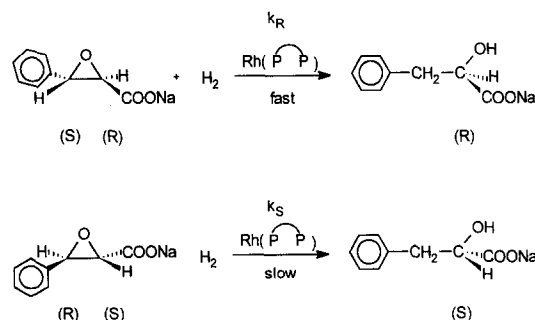
Scheme 5. Kinetic resolution in the hydrogenolysis of sodium *trans*-phenylglycidate.

Thus, it appears that aqueous catalytic asymmetric hydrogenolysis could be a useful synthetic method for both the preparation of chiral *trans*-disubstituted epoxides and α-hydroxycarboxylic acids. However, for this goal, the optical yields of such reactions are yet to be improved by using more efficient ligands than the BDPP derivatives.

3. Experimental

3.1. General

All operations with catalysts and ligands were carried out by using Schlenk type glassware under Ar. (S,S)-BDPP [31], sulfonated BDPP derivatives [7,20], (S)-(−)-MTPA chloride [32], disodium *cis*-epoxysuccinate [33], sodium *trans*-phenyl-glycidate [34] and the diastereomers of (S)-1-phenyleth- ylamine salt of (2S,3R)- and (2R,3S)-*trans*-3-phenylglycidic acid [33] were prepared as previously described. Deuterium gas was obtained from Alphagas. The hydrogenolysis reactions were carried in 20 ml stainless steel shaker tube reactors. ^{1}H-NMR spectra of diastereomeric esters of (R)-(+)-α- methoxy-α-(trifluoromethyl)phenylacetic acid in the case of malic acid and diastereomeric salt of (S)-1-phenylethylamine salt of (2S,3R)- and (2R,3S)-*trans*-3-phenylglycidic acid for the determina- tion of the optical yield were recorded on a Varian XL instrument at 400 MHz. Otherwise, Bruker AMX-300 and Varian Unity 300 instruments were used at an equivalent ^{1}H frequency of 300 MHz for recording NMR spectra. The high pressure NMR spectra were recorded in a home-built assembly consisting of a 10 mm sapphire tube and titanium head, which has been recently described [35]. [31]P detected reversed [103]Rh-NMR spectra were obtained by using a Bruker AC 100 instrument with a technique reported in literature [25].

3.2. Hydrogenolysis

A 12.3 mg (0.025 mmol) amount of cyclooctadiene dimer [Rh(COD)Cl]$_2$ and 0.055 mmol of sulfonated BDPP were dissolved in 10 ml of degassed H$_2$O/AcOEt (1:1) in a Schlenk tube, under an argon atmosphere. The two-phase mixture was stirred for 20 min and then 0.88 g (5 mmol) of disodium *cis*-epoxisuccinate (or *trans*-phenylglycidate) was added. The mixture was injected into a 20 ml stainless steel autoclave under argon. The reaction vessel was then flushed and pressurised with hydrogen. The contents were shaken for 6 h at room temperature.

For the determination of conversion and enantiomeric excess (ee), the aqueous phase of the reaction mixture was separated and then passed through a column packed with ion-exchange resin (H$^+$ form). The column was washed with water (30 ml). The water was then evaporated under reduced pressure and the solid residue was dissolved in methanol and treated with diazomethane. Both the conversion of epoxide and the ee of the formed malic acid in the form of methyl ester were determined by chiral GLC on a CP-cyclodextrin-B-2,3,6-M-19 column (25 m, 0.25 mm id, Chrompack) using argon as a carrier gas, under the following conditions: oven temperature from 110°C (initial time: 2 min) to 250°C, with heating rate of 2°C/min (2-hydroxy-succinic acid dimethyl ester was base-line resolved). The prevailing R configuration of the product gave the smaller retention time. Several instances, the ee was also determined by ^{1}H-NMR spectroscopy after derivatisation of the product. For this purpose, the hydroxyl group was esterified with (S)-MTPA chloride [32] to give the Mosher ester derivatives (Eq. (3)). The ee values of this ester was obtained from the methyl protons in the ^{1}H-NMR spectrum. The absolute configuration of the product acid was assigned on the basis of

the spectra of the Mosher derivatives obtained from the commercially available enantiomerically pure malic acid.

$$\text{(3)}$$
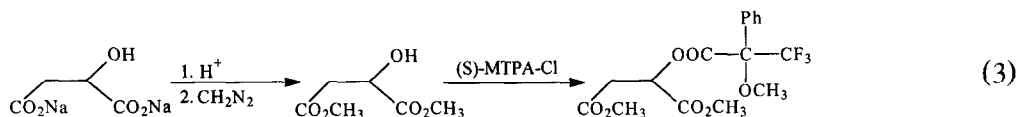
The hydrogenolysis of *trans*-phenylglycidate and the analysis of the product were carried out in an analogous manner. The enantiomeric excess of the remaining substrate was determined by chiral solvating agent (CSA: (S)-1-phenylethylamine).

3.3. ^{1}H-NMR data of succinic acid and phenylglycidic acid derivatives

3.3.1. Sodium cis-epoxysuccinate
^{1}H-NMR (D$_2$O): δ 3.7 (s, 1H, CH); ^{13}C-NMR: δ 57.7 (s, CH), 177.47 (s, COONa).

3.3.2. (S)-2-O((R)-MTPA)-succinic acid dimethyl ester
^{1}H-NMR (CDCl$_3$): δ 2.93 (dd, $^2J = 16.9$ Hz, $^3J = 9.1$ Hz, 1H, CH$_2$), 3.02 (dd, $^2J = 16.9$ Hz, $^3J = 3.8$, 1H, CH$_2$), 3.56 (q, $^5J_{F-H} = 1.2$ Hz, 3H, CH$_3$), 3.70 (s, 3H, CH$_3$), 3.77 (s, 3H, CH$_3$), 5.71 (dd, $^2J = 9.1$ Hz, $^2J = 9.1$ Hz, $^2J = 3.8$ Hz, 1H, CH).

3.3.3. (R)-2-O((R)-MTPA)-succinic acid dimethyl ester
^{1}H-NMR (CDCl$_3$): δ 2.88 (dd, $^2J = 16.7$ Hz, $^3J = 8.7$, 1H, CH$_2$), 2.96 (dd, $^2J = 16.7$ Hz, $^3J = 4.1$ Hz, 1H, CH$_2$), 3.59 (s, 3H, CH$_3$), 3.64 (q, $^5J_{F-H} = 1.2$ Hz, 3H, CH$_3$), 3.82 (s, 3H, CH$_3$), 5.73 (dd, $^3J = 8.7$ Hz, $^3J = 4.1$ Hz, 1H, CH).

3.3.4. (RS)-2-hydroxy-succinic acid dimethyl ester
^{1}H-NMR (CDCl$_3$): δ 2.80 (dd, $^2J = 16.5$ Hz, $^3J = 6.1$ Hz, 1H, CH$_2$), 2.88 (dd, $^2J = 16.5$ Hz, $^3J = 4.3$ Hz, 1H, CH$_2$), 3.73 (s, 3H, CH$_3$), 3.82 (s, 3H, CH$_3$), 4.51 (dd, $^3J = 6.1$ Hz, $^3J = 4.3$ Hz, 1H, CH).

3.3.5. (RS)-3-deuterio-2-hydroxy-succinic acid dimethyl ester
^{1}H-NMR (CDCl$_3$): δ 2.83 (dtr, $^2J = 4.1$ Hz, $^2J_{H-D} = 2.1$ Hz, 1H, CH$_2$), 3.73 (s, 3H, CH$_3$), 4.51 (d, $^3J = 4.1$ Hz, 1H, CH).

3.3.6. 3-Deuterio-2 hydroxy succinic acid sodium salt
^{1}H-NMR (D$_2$O): 2.83 (q, $^3J = 4.2$ Hz, $^2J_{H-D} = 2.4$ Hz, 1H, CHD), 4.52 (d, $^3J = 4.2$ Hz, 1H, CH); ^{13}C-NMR: δ 45.0 (tr, $^1J_{C-D} = 20.0$ Hz, CHD), 182.65 (s, COONa), 183.8 (s, COONa).

3.3.7. Sodium trans-3-phenylglycidate
^{1}H-NMR (D$_2$O): δ 3.98 (d, $^3J = 2.2$ Hz, 1H, CH), 3.57 (d, $^3J = 2.2$ Hz, 1H, CH), 7.2–7.5 (m, 5 H, Ph).

3.3.8. (S)-1-Phenylethylamine salt of (2R,3S)-trans-3-phenylglycidic acid

^{1}H-NMR (CDCl$_3$): δ 1.57 (d, $^3J = 7$ Hz, 3H, CH$_3$), 3.19 (d, $^3J = 1.7$ Hz, 1H, CH), 3.58 (d, $^3J = 1.7$ Hz, 1H, CH), 4.32 (q, $^3J = 7$ Hz, 1H, CH), 7.3–7.4 (m, 10 H, Ph).

3.3.9. (S)-1-phenylethylamine salt of (2S,3R)-trans-3-phenylglycidic acid

^{1}H-NMR (CDCl$_3$): δ 1.57 (d, $^3J = 7$ Hz, 3H, CH$_3$), 3.16 (d, $^3J = 1.7$ Hz, 1H, CH), 3.48 (d, $^3J = 1.7$ Hz, 1H, CH), 4.32 (q, $^3J = 7$ Hz, 1H, CH), 7.3–7.4 (m, 10 H, Ph).

3.3.10. Sodium 2-hydroxy-3-phenylpropionate

^{1}H-NMR (D$_2$O): δ 2.86 (dd, $^2J = 13.9$ Hz, $^3J = 8.2$ Hz, 1H, CH$_2$), 3.09 (dd, $^2J = 13.9$ Hz, $^3J = 4.1$ Hz, 1H, CH$_2$), 4.25 (dd,, $^2J = 4.1$ Hz, $^2J = 8.2$ Hz, 1H, CH), 7.2–7.5 (m, 5 H, Ph).

3.4. Deuterium labelling and NMR experiments

The deuterium exchange experiments were carried out in a 20 ml stainless steel autoclave as described above in Section 3.2, except that deuterium gas (20 bar) or heavy water was used instead of hydrogen or water, respectively. The isotopic composition of H/D in the product was then analyzed after similar work-up by ^{1}H- and ^{13}C-NMR spectroscopy. The structural studies by NMR spectroscopy by using BDPP$_{TS}$ were also coupled with deuterium exchange experiments. For this purpose, a 0.025 mmol amount of [Rh(COD)Cl]$_2$ (12.3 mg) and 0.055 mmol of sulfonated BDPP$_{TS}$ were dissolved in a mixture of 4 ml D$_2$O– or H$_2$O–EtOAc (1/1) in a Schlenk tube. After about 10 min stirring at room temperature when the organic phase became colourless, the orange yellow deuterious or aqueous phase was transferred into a high pressure NMR tube. A ^{31}P-NMR spectrum was then recorded under nitrogen and the tube was pressurized with 20–40 bar of H$_2$ or D$_2$, respectively. The hydrogenation (deuteriation) of the precursor diene complex was followed by using a kinetic program for recording ^{31}P-NMR spectra. When the transformation of the diene complex was complete (ca. 40 min at rt) the pressure was released. A stoichiometric (0.05 mmol) or a catalytic (0.5 mmol) amount of epoxysuccinate was then added under nitrogen. In the latter case, the tube was pressurized again with the same gas and further kinetic ^{13}C- and ^{31}P-spectra were recorded, while in stoichiometric experiments the reaction was followed under atmospheric nitrogen pressure. In the catalytic experiments in D$_2$O and H$_2$O, ^{1}H- and ^{2}H-NMR spectra, respectively, were also recorded periodically, which could be used with the ^{13}C-NMR spectra for the estimation of H/D exchange. ^{103}Rh-NMR spectra were obtained from stoichiometric experiments. The rest of the NMR spectra related to the formation of Rh–COD complexes containing BDPP$_{MS}$ and BDPP$_{DS}$ were recorded at similar concentrations in usual 10 mm glass tubes. ^{31}P- and ^{103}Rh-NMR data are given above.

3.4.1. Rhodaoxetane

^{13}C-NMR: δ 20.8 (m, CH$_3$), 39.2 (m, CH$_2$), 32.0 (m, CH), 60.8 (s, C-1), 76.2 (d m, $^2J_{P–C} = 83$ Hz, 183–186 (m, COONa); ^{31}P-NMR: P$_1$ δ 35–40, P$_2$ 40–44, $^1J_{Rh–P} = 126$ Hz, 136 Hz; 129Hz, 131 Hz; 126 Hz, 130 Hz; 120 Hz, 139 Hz; $^2J_{P–P} = 42$ Hz; ^{103}Rh-NMR: d 1944, 1929, 1916, 1887.

Acknowledgements

References

[1] I.T. Horváth and F. Joó, NATO ASI 3. Ser. 5 (1995) 1.

[2] E.G. Kuntz, CHEMTECH (1987) 570.

[3] F. Joó and Z. Tóth, J. Mol. Catal. 8 (1980) 369.

[4] D. Sinou, Bull. Soc. Chim. Fr. (1987) 480.

[5] S. Ahrland, J. Chatt, N.R. Davies and A.A. Williams, J. Chem. Soc. (London) (1958) 276.

[6] A.F. Borowski, D.J. Cole-Hamilton and G. Wilkinson, Nouv. J. Chim. 2 (1977) 137.

[7] Y. Amrani, L. Lecomte, D. Sinou, J. Bakos, I. Tóth and B. Heil. Organometallics 8 (1989) 542.

[8] L.D. Petit, and H.M.N.H. Irving, J. Chem. Soc. (London) (1964) 5336.

[9] M.J.H. Russel, Platinum Metal Rev. 32 (1988) 179.

[10] B.A. Murrer, DE 3 135 127 A1 to Johnson Matthey.

[11] G. Schwarzenbach and M. Schellenburg, Helv. Chim. Acta 48 (1965) 28.

[12] K.N. Harrison, P.A.T. Hoye, A.G. Orpen, P.G. Pringle and M.B. Smith, J. Chem. Soc., Chem. Commun. (1989) 1096.

[13] R.T. Smith, R.K. Ungar and M.C. Baird, Trans. Met. Chem. 7 (1982) 288.

[14] I. Tóth and B.E. Hanson, Tetrahedron: Asymmetry 1 (1990) 895.

[15] I. Tóth and B. Hanson and M. Davis, Tetrahedron: Asymmetry 1 (1990) 913.

[16] T. Okano, I. Uchida, T. Nakagaki, H. Konishi and J. Kiji, J. Mol. Catal. 54 (1989) 65.

[17] E. Kuntz, Ger. Offen 2 700 904, 1977.

[18] G. Mignani, D. Morel and Y. Colleuille, Tetrahedron Lett. 26 (1985) 6337.

[19] M. Safi and D. Sinou, Tetrahedron Lett. 32 (1991) 2025.

[20] J. Bakos, B. Heil, Á. Orosz, M. Laghmari, P. Lhoste and D. Sinou, J. Chem. Soc., Chem. Commun. (1991) 1684.

[21] A.S.C. Chan and J.P. Coleman, J. Chem. Soc., Chem. Commun. (1991) 535.

[22] C. Lensink and J.G. de Vries, Tetrahedron: Asymmetry 3 (1992) 235.

[23] G. Strathdee and R. Given, Can. J. Chem. 52 (1974) 2216 and 2226.

[24] P.S. Pregosin and R.W. Kunz, in: ^{31}P and ^{13}C NMR of Transition Metal Phosphine Complexes, ed. P. Diehl, E. Fluck and R. Kosfeld (Springer-Verlag, Berlin, 1979).

[25] C.J. Elsevier, J.M. Ernsting and W.G.J. de Lange, J. Chem. Soc., Chem. Commun. (1989) 585.

[26] M.J. Calhorda, A.M.Galvao, C. Unalerogru, A.A. Zlota, F. Frolow and D. Milstein, Organometallics, 12 (1993) 3316.

[27] A.S.C. Chan and J. Halpern, J. Am. Chem. Soc. 102 (1980) 838.

[28] J.M. Brown and P.A. Chaloner, J. Chem. Soc., Chem. Commun. 344 (1980).

[29] W.A. Herrmann, J.A. Kulpe, W. Konkol and H. Bahrmann, J. Organomet. Chem. 389 (1990) 85.

[30] V.S. Martin, S.S. Woodard, T. Katsuki, Y. Yamada, M. Ikeda and K.B. Sharpless, J. Am. Chem. Soc. 103 (1981) 6237; C.-S. Chen, Y. Fujimoto, G. Girdaukas and C.J. Sih, J. Am. Chem. Soc. 104 (1982) 7294.

[31] J. Bakos, I. Tóth, B. Heil and L. Markó, J. Organomet. Chem. 279 (1985) 23.

[32] J.A. Dale, D.L. Dull and H.S. Mosher, J. Org. Chem. 34 (1969) 3543.

[33] G.B. Payne and B. Williams, J. Org. Chem. 24 (1959) 54.

[34] K. Harada, J. Org. Chem. 31 (1966) 1407.

[35] C.J. Elsevier, J. Mol. Catal. 92 (1994) 285.