Asymmetric isomerization of allylic compounds and the mechanism

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Abstract—Rhodium(I) complexes of the type \([\text{Rh(diphosphine)}L_n]ClO_4\) \((L_n = n/2 \text{ molecules of solvent, diene, or diphosphine})\) are effective catalysts for 1,3-hydrogen migration of functionalized allylic compounds such as allylamines, allyl alcohols, allyl ethers, etc., and chiral diphosphine complexes cause asymmetric isomerizations. Per-aryldiphosphine with \(C_2\) symmetry, \text{binap}, is the most effective ligand in all aspects and allylamine is the most suitable substrate; various kinds of allylamines are isomerized selectively to optically active \((E)\)-enamines or imines with virtually perfect enantioselectivity (95–99 %ee) in high yields. Deuterium labeling experiments showed that this asymmetric isomerization of allylamines proceeds via highly stereospecific intramolecular 1,3-hydrogen migration. On the basis of the reaction intermediates detected by \(^{31}P\) as well as \(^1H\) NMR spectra and kinetic studies a plausible reaction mechanism is proposed for the catalysis. It is also concluded that the enantioselection is made at a stage of kinetically unimportance.

INTRODUCTION

Several transition metal complexes have been reported as effective catalysts for isomerization of functionalized allylic compounds (ref. 1). Almost all of them, however, have only poor or no catalytic activity for the isomerization of allylic compounds having a trisubstituted olefin of the type \(1\) \((R_1, R_2 \neq H)\) (ref. 2), an essential substrate to achieve asymmetric isomerization and only a few examples of the asymmetric isomerization with very low optical inductions are available (ref. 3). Recently we have developed a highly efficient asymmetric isomerization of allylamine catalyzed by cationic rhodium(I) complexes of an optically active diphosphine (ref. 4). Here I want to describe the specific feature of the asymmetric catalysis, its extension to asymmetric isomerization of other allylic compounds, and the mechanistic aspects of the asymmetric isomerization of allylamines.

ASYMMETRIC ISOMERIZATION OF ALLYLAMINE

Cationic rhodium(I) complexes of the type \([\text{Rh(diphosphine)}L_n]^+\) \((L_n = n/2 \text{ molecules of solvent or diene})\) are efficient isomerization catalysts for \text{tert-} and \text{sec-}allylamine to enamine or
imine (ref. 4). In this isomerization only (E)-enamines were produced selectively. The catalytic activity is very sensitive to the property of a diphosphine ligand as well as to the kind of ligand $L_2$. That decreases in the order significantly: per-aryldiphosphine $> \text{Ar}_2P-X-P\text{Ar}_2$ ($-X$ = alkylene group) $> \text{per-alkyldiphosphine}$. A fully arylated diphosphine with $C_2$ chirality, binap (6) (ref. 5), was found to be the best ligand with respect to its activity and selectivity. For examples, the rhodium complex $[\text{Rh(binanap)}(\text{cod})\text{ClO}_4$ (cod = 1,5-cyclooctadiene) isomerizes diethylnerylamine (7) or diethylgeranylamine (8) in THF to citronellal (E)-diethylenamine (9) in a yield over 96 % under fairly mild conditions (40–60 °C, 20 h), the double bond at C(6) being unaffected. The solvent complex $[\text{Rh(binanap)}(S)_n]^+ (S = \text{solvent})$, which is prepared in situ from the diene complex by treating with hydrogen, is more active and the isomerization took place even at low temperature below −20 °C, though slowly (see below). When a diphosphine is used as $L_2$, the catalytic activity drops drastically and a bis(diphosphine) complex $[\text{Rh-(diphos)}_2]\text{ClO}_4$ did not show any catalytic activity for the isomerization of 7 even at 120 °C, 18 h. If binap is employed as a diphosphine ligand, the bis(diphosphine) complex $[\text{Rh-(binap)}_2]\text{ClO}_4$ showed also sufficiently high catalytic activity for the isomerization above 90 °C (ref. 6).

The first enantioselective hydrogen migration of tert-allylamine using cobalt complexes of a chiral diphosphine has been reported by Otsuka's group (ref. 7). The chemical and optical yields for the isomerization of 7 or 8, however, were at most 12 % and 30 %ee, respectively. A cationic rhodium complex of binap, $[\text{Rh(binanap)}(\text{cod})]\text{ClO}_4$ showed also excellent enantioselectivity for the isomerization of allylamines: 7 or 8 is convertible to an optically active (E)-enamine 9 in 95 to 99 %ee. A beautiful stereochemical correlation between the substrate geometry, chirality of binap, and the product configuration is present as shown in Scheme 1. Besides the diene complex, both $[\text{Rh(binanap)}(S)_n]^+$ and $[\text{Rh(binanap)}_2]^+$ gave equally high enantioselectivity in the same direction for the isomerization as the diene complex, though the catalytic activity varies considerably according to the catalyst precursors. As is obvious from the mirror image correlation, in order to obtain maximum optical yields it is essential to use isomerically pure substrates and enantiomerically pure binap. With highly purified reagents the optical yields of the isomerization of 8 by the (−)-binap-rhodium catalyst exceeded 99.0 % for a wide range of temperature (below 80 °C), the 3R configuration being produced. The temperature invariability of the chiral recognition is amazing. Above 100 °C, the optical yield starts to decrease slowly (98 %ee at 100 °C, 95 %ee at 140 °C). The present asymmetric isomerization of 8 is employed as a key step of the industrial production of...
Asymmetric isomerization of allylic compounds

SCHEME 1

\[
\begin{align*}
R & \quad \text{NEt}_2 \\
\text{Z} & \quad \text{NET}_2 \quad \text{[Rh)((S)-(S)-binap)]}^+ \\
\text{E} & \quad \text{NET}_2 \quad \text{[Rh((R)-(S)-binap)]}^+ \\
\end{align*}
\]

\( R = (\text{CH}_3)_2\text{C}=\text{CHCH}_2\text{CH}_2, \) simple alkyl, \( \text{C}_6\text{H}_5, \) etc.

1-menthol (Ref. 8). Several representative results are summarized in Table 1. A secondary allylamine (10) was also isomerized by the present catalyst to give the corresponding optically active imine (11) in very high chemical and optical yields. As for the substrate allylamine (3), simple alkyl, phenyl, or hydroxyalkyl group besides prenylmethyl group can be employed as the substituent \( \text{R}^1 \). N-Phenyl- and N,N-diphenylallylamine, however, do not undergo the isomerization with the cationic rhodium(I) complexes. These results suggest the importance of nitrogen basicity in the substrate for effective catalysis.

ISOMERIZATION OF OTHER ALLYLIC COMPOUNDS

The cationic rhodium(I) complex \([\text{Rh(diphosphine)}]^{+}\) serves as an active catalyst also for isomerization of allylic compounds other than allylamines; e.g., allyl alcohol, allyl ether, or N-allylamide. In these isomerization also, binap is the best choice as a diphosphine ligand and several representative results are summarized in Table 2. Primary and secondary allylic alcohols isomerize smoothly to aldehydes and ketones respectively, though the yields of aldehydes are not so high due to further transformation of the product aldehydes in the presence of rhodium complexes. With a rhodium complex \([\text{Rh}((+)-\text{binap})(\text{cod})]^{+}\) allyl alcohols of the type 1 (\( \text{R}^1, \text{R}^2 \neq \text{H}, \text{X} = \text{OH} \)) can be smoothly isomerized to optically active aldehydes (eq.

\[
\begin{align*}
\text{12} & \quad \text{[Rh((+)-binap)(cod)]}^+ \\
& \quad \text{THF, 60 °C, 24h} \\
\text{13} & \quad \text{Chem. yield 70 \%,} \\
& \quad \text{Opt. yield 37 \%ee} \\
\text{14} & \quad \text{[Rh((+)-binap)(cod)]}^+ \\
& \quad \text{THF, 60 °C, 24h} \\
\text{15} & \quad \text{Chem. yield 47 \%,} \\
& \quad \text{Opt. yield 53 \%ee} \\
\end{align*}
\]

3,4). The optical yields, however, are very low compared with those realized in the isomerization of prochiral allylamines, though much higher than the hitherto reported examples of the asymmetric isomerization of allyl alcohols (Ref. 3). Noteworthy is the fact that even an alcohol having a styrene-type conjugation can be isomerized (eq. 4). The stereochemical correlations were the same with those observed for the isomerization of allylamine. Isomerization of allyl phenyl ether and allylacetamid amide, however, produced \( E/Z \) mixtures of an enol ether and an enamide.
TABLE 1. Asymmetric isomerization of allylamines catalyzed by $[\text{Rh(binap)}]^{\text{ClO}_4}$

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Catalyst</th>
<th>Product</th>
<th>Chemical yield (%)</th>
<th>Optical yield (%ee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$[\text{Rh}(\langle-\rangle\text{-binap})(S))^{\text{+}}$</td>
<td>(S)-9</td>
<td>95</td>
<td>93</td>
</tr>
<tr>
<td>&quot;</td>
<td>$[\text{Rh}(\langle+\rangle\text{-binap})(\text{S}))^{\text{+}}$</td>
<td>(R)-9</td>
<td>94</td>
<td>95</td>
</tr>
<tr>
<td>&quot;</td>
<td>$[\text{Rh}(\langle+\rangle\text{-binap})(\text{cod}))^{\text{+}}$</td>
<td>&quot;</td>
<td>13</td>
<td>96</td>
</tr>
<tr>
<td>&quot;</td>
<td>$[\text{Rh}(\langle-\rangle\text{-binap})(\text{cod}))^{\text{+}}$</td>
<td>(S)-9</td>
<td>97</td>
<td>92</td>
</tr>
<tr>
<td>8</td>
<td>$[\text{Rh}(\langle+\rangle\text{-binap})(\text{cod}))^{\text{+}}$</td>
<td>&quot;</td>
<td>94</td>
<td>96</td>
</tr>
<tr>
<td>&quot;</td>
<td>$[\text{Rh}(\langle-\rangle\text{-binap})(\text{cod}))^{\text{+}}$</td>
<td>(R)-9</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>&quot;</td>
<td>$[\text{Rh}(\langle-\rangle\text{-binap})(\text{cod}))^{\text{+}}$</td>
<td>&quot;</td>
<td>100</td>
<td>98</td>
</tr>
</tbody>
</table>

$\text{NHcy(10)}[\text{Rh}(\langle+\rangle\text{-binap})(\text{cod}))^{\text{+}}$ $\text{NHcy(11)}$ 100 96

$\text{Ph}\text{NMMe}_2[\text{Rh}(\langle+\rangle\text{-binap})(\text{cod}))^{\text{+}}$ $\text{Ph}\text{NMMe}_2$ 83 90

$\text{R}\text{NET}_2[\text{Rh}(\langle-\rangle\text{-binap})(\text{cod}))^{\text{+}}$ $\text{R}\text{NET}_2$ 95 97 $h$

$\text{HO}\text{NET}_2[\text{Rh}(\langle-\rangle\text{-binap})(\text{cod}))^{\text{+}}$ $\text{HO}\text{NET}_2$ 98 (+12°) $i$

$^a$ [Substrate] = 0.44 M, [substrate]/[Rh] = 100, 40 °C, 23 h, in THF unless otherwise noted.

$^b$ $S = \text{solvent}; \text{nbd} = \text{norbordiene}$. $^c$ [Substrate]/[Rh] = 176. $^d$ [Substrate] = 2.5 M, [substrate]/[Rh] = 8,000, 80 °C, 4 h. $^e$ [Substrate] = 2.3 M, [substrate]/[Rh] = 8,000, 100 °C, 15 h. $^f$ 60 °C, 48 h. $^g$ [Substrate] = 2.3 M, [substrate]/[Rh] = 2,000, 100 °C, 15 h. $^h$ $R = \text{ref. 9}$. $^i$ [a]D = +14.9° of the hydrolyzed aldehyde. The reported maximum rotation is +14.9° (ref. 10).

TABLE 2. Isomerization of allylic compounds catalyzed by $[\text{Rh(diphosphine)}]^{\text{ClO}_4}$

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Product</th>
<th>Catalyst</th>
<th>Conversion (%)</th>
<th>Selectivity (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{OH}$</td>
<td>$\text{CHO}$</td>
<td>$[\text{Rh(binap)}]^{\text{+}}$</td>
<td>64</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>$[\text{Rh(binap)(S))^{\text{+}}$</td>
<td>88</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>$[\text{Rh(dppb)(S))^{\text{+}}$</td>
<td>50</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>$[\text{Rh(dipb)(S))^{\text{+}}$</td>
<td>42</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>$\text{OH}$</td>
<td>$\text{CHO}$</td>
<td>&quot;</td>
<td>99</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>$\text{OH}$</td>
<td>$\text{O}$</td>
<td>&quot;</td>
<td>87</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>$\text{OH}$</td>
<td>$\text{O}$</td>
<td>&quot;</td>
<td>88</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>$\text{OH}$</td>
<td>$\text{O}$</td>
<td>&quot;</td>
<td>82</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>$\text{OPh}$</td>
<td>$\text{OPh}$</td>
<td>&quot;</td>
<td>100</td>
<td>97</td>
<td>E/Z = 87/13</td>
</tr>
<tr>
<td>$\text{NHCOCH}_3$</td>
<td>$\text{NHCOCH}_3$</td>
<td>&quot;</td>
<td>42</td>
<td>89</td>
<td>E,Z mixture</td>
</tr>
</tbody>
</table>

$^a$ [Substrate] = 0.2 M, [substrate]/[Rh] = 200, 60 °C, 24 h, in THF. $^b$ dppb = Ph$_2$P(CH$_2$)$_4$PPh$_2$; dipb = (i—Pr)$_2$P(CH$_2$)$_4$P(i—Pr)$_2$; $S = \text{solvent}$. 
MECHANISTIC ASPECTS ON THE ASYMMETRIC ISOMERIZATION OF ALLYLAMINE

Labeling experiments. It is generally recognized that the transition metal catalyzed olefin isomerizations proceed via one of two distinct sequences; the reversible addition-elimination of M-H to the double bond, leading to 1,2-hydrogen shift and the π-allyl mechanism, resulting in 1,3-hydrogen shift (ref. 1b). Isomerization of 1,1-dideuterated allylamine (16-d2) catalyzed by [Rh(binap)(cod)ClO4 gave exclusively 1,3-dideuterated enamine (17-d2). In addition, the isomerization in the presence of an equal amount of the parent nondeuterated allylamine (16) produced only a mixture of an enamine 17 and its dideuterated compound 17-d2. Careful investigation of the reaction products by 1H NMR and GC-MS analyses showed the absence of mono-deuterated products (eq. 5). Therefore it is concluded that the present isomerization proceeds exclusively via intramolecular 1,3-hydrogen shift. These results strongly favor the π-allyl mechanism. Next we performed the isomerization of an enantiomerically labeled allylamine in order to see "Which enantiotopic hydrogen at C(1) does migrate to C(3)?" An isotopically labeled compound, (R)-diethylgeranyl-1-d-amine ((R)-18) was prepared from prenyl-acetone (19) in seven steps by the sequence outlined in Scheme 2 and the optical purity was assessed to be ca. 93 % based on the optical purity of the parent primary geranyl-1-d-amine ((R)-25) determined by 400 MHz NMR analysis of its (R)-α-methoxy-α-(trifluoromethyl)phenyl-acetamide using a triple resonance technique. The isomerization of (R)-18 catalyzed by [Rh(=)-binap(S)2]+ in THF (40 °C, 40 h) showed that the C(1) proton moved selectively to C(3) to give (R,E)-citronellal enamine, (R)-9-1-d. The reaction catalyzed by the (+)-binap-rhodium complex resulted likewise in the formation of (S)-9-3-d via deuterium migration. The 1H and 2H NMR analyses of these products revealed that the enantiospecificity of the 1,3-hydrogen migration was more than 97 %. No deuterium isotope effect was detected within the limit of accuracy of the present NMR analyses. The formal stereorelationship of the geranylamine substrate and the E enamine is illustrated in Scheme 3. If one assumes a hypothetical, canonical s-trans conformation for the geranylamine (with respect to the C(2)=C(3) double bond and the diethylamino group), the 1,3-hydrogen shift is viewed to be occurring in a suprafacial manner.

SCHEME 2

Legend: Ag2CO3/Cellite = silver carbonate/cellite; Borane or (S)-BINAL-H = borane or (S)-binalehydride; CDO = cellotriose kinase; D = deuterium; D2 = deuterium-rich water; E = enamine; Ph = phenyl; PhNMe2 = diphenylmethyl.
**Scheme 3**

[Diagram of Scheme 3]

**1H and 31P NMR Studies.** Both 31P and 1H NMR measured at -80 °C to 40 °C of a mixture of a catalyst [Rh(binap)(cod)]ClO₄ and 7 in THF-d₈ did not give any useful information concerning the reaction intermediates. A doublet signal of the COD complex in the 31P NMR spectrum was not affected appreciably by addition of the substrate 7 during the whole temperature range. A 1H NMR spectrum of a 1:2 mixture of the COD complex and 7 was essentially the same as a sum of the individual spectra below 0 °C except for slight down-field-shifts (Δδ ~0.15) of signals due to α-methylene protons of neryl and N-ethyl groups of 7. This suggests weak interaction of 7 with the rhodium complex through the nitrogen lone pair. Above 0 °C, isomerization took place and the signals due to the product enamine 9 appeared gradually. In order to get more detailed information about the reaction intermediates a more labile solvent complex was employed. Thus a 1:1 mixture of [Rh((+)-binap)(MeOH)₂]ClO₄ and 8 in acetone-d₆ (0.01 M each) was prepared at -90 °C (Note 1). The 31P NMR spectra (161 MHz) measured at -80 °C indicated only a doublet signal at δ 53.25 (JRh_p = 199.5 Hz) due to the bis(acetone) complex [Rh((+)-binap)(acetone-d₆)₂]ClO₄ (Note 2). The 1H NMR spectrum showed signals quite similar to those of the free allylamine 8 except for broadening of the signals at δ 3.00, 2.45, and 0.95 due to C(1) methylene and N-ethyl protons. These phenomena suggest the presence of a rapid equilibrium between the bis(acetone) complex and an N-coordinated substrate complex, e.g. [Rh((+)-binap)(acetone-d₆)(8)]⁺ (designated as [Rh(binap)(N-A)(S)]⁺) (Note 3). At -60 °C, a set of two double doublets centered at δ 30.42 (JRh_p = 193.7 Hz, Jpp = 58.7 Hz) and 49.87 (JRh_p = 193.7 Hz) gradually appeared on consumption of the doublet signal due to the bis(acetone) complex. This signal set was also observed when (S)-9 was added to the complex [Rh((+)-binap)(MeOH)₂]ClO₄ at -40 °C, indicating that these signals are due to an enamine-Rh⁺ complex, which may contain a chelate-coordinated enamine (designated as [Rh(binap)(N=E)]⁺) (ref. 11). At this stage a new doublet appeared at δ 51.22 (JRh_p = 195.6 Hz) which was tentatively assigned to bis(enamine) complex (designated as [Rh(binap)(N-E)₂]⁺). At higher temperature, the change in NMR spectra proceeded more smoothly. The 31P NMR spectrum taken after complete consumption of the starting allylamine at 0 °C was shown in Fig. 1a in which there observed an intense eight-line signal and a weak doublet at δ 51.22 (JRh_p = 195.6 Hz)

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**Note 1.** Acetone-d₆ was used as a solvent instead of THF-d₈, because the bis(methanol) complex, when dissolved in THF without substrate, gave sparingly soluble solids and acetone can also be used as an effective solvent for the catalysis.

**Note 2.** Chemical shifts were recorded relative to external 85% phosphoric acid. The spectra of the standard were taken before and after each measurement of the spectra of samples. When the 31P NMR spectra (40.25 MHz) were run using a 3-5% methanol-d₄ solution of phosphoric acid in a coaxial sealed capillary as an external standard each signal appeared at ca. 2.84 ppm higher-field position.

**Note 3.** The 1H NMR spectrum (100 MHz, measured at -40 °C immediately after sample preparation) of a more concentrated sample (ca. 0.1 M of [Rh((+)-binap)(MeOH)₂]ClO₄ and 0.1M of 8) showed slight down-field-shifts of the α-methylene protons of geranyl and N-ethyl groups (Δδ ~0.3), which suggest weak coordination of 8 through nitrogen lone pair. For an N-coordinated substrate complex, a five-coordinated complex [Rh(binap)(N-A)(S)]⁺ is also possible.
Asymmetric isomerization of allylic compounds

31P NMR.

Fig. 1 31P(161 MHz) (a) and 1H NMR(400 MHz) (b) of a mixture of 8 (0.01M) and [Rh((+)—binap)(MeOH)2]ClO4 (0.01M) in acetone-d6 after reaction at 0 °C, 2h.

in addition to a doublet at δ 53.25 (J_{Rh-P} = 199.5 Hz) due to the starting bis(acetone) complex. If an excess of substrate was employed, the spectrum resulted in only a doublet signal of the bis(enamine) complex. Even at −80 °C, the doublet signal of the starting bis(acetone) complex changed slowly and after 900 h converted completely to a set of the eight—line signals but no further change was observed at this temperature (Note 4). The 1H NMR spectrum (400 MHz) of this sample (Fig. 1b), though complex, exhibited a doublet at δ 0.33 (J = 6.4 Hz), two triplets at δ 0.64 (J = 7.3 Hz) and 0.90 (J = 7.0 Hz), which supports the formation of an enamine-Rh⁺ complex. Despite careful search, no 1H signal assignable to the metal—hydride was detected, implying that a hydride π—allyl complex, if formed, would not be stable enough for NMR detection. These observations suggest that in the methanol complex—catalyzed reaction transformation of [Rh(binap)(N—lr_E)]⁺ to an active catalyst, e.g., [Rh(binap)(S)2]⁺ (S = solvent or allylamine) producing enamine should be the rate-determining.

Kinetic studies

The rates of isomerization of 7 using [Rh((±)—binap)(cod)]ClO4 in THF-d8 and [Rh((+)—binap) (MeOH)2]ClO4 in acetone-d6 as catalysts were measured by monitoring the 1H NMR signals of the substrate and product, because the reaction proceeds very cleanly and gave only 9 as the sole detectable product. The two reactions follow different rate laws. The initial rate dependence on the catalyst concentration was 1st order for both cases. For the COD complex catalyzed isomerization the initial rate dependence on the initial substrate concentration was as shown in Fig. 2 and the rate follows equation 6, where R₀, [A]₀, and [C] are the initial rate, initial substrate and catalyst concentration respectively (k and K are constants).

\[ R_0 = k[C][A]_0/(1 + K[A]_0) \]

\[ [A]_0 = 0.05 - 0.55 \text{ M}; [C] = 0.82 - 4.05 \text{ mM} \]

For the bis(methanol) complex catalyzed isomerization, however, the initial rate dependence was rather peculiar as shown in Fig. 3. The rate can be described in terms of a composite equation (eq. 7), where [S] is the solvent concentration (k'and k'' are constants).

Note 4. 31P NMR of a mixture of [Rh((+)—binap)(MeOH)2]ClO4 and 7 in acetone showed also a similar spectral change and gave a set of similar eight-line signals at slightly lower field (Δδ 0.6—0.4) due to a diastereomer of the enamine complex obtained from 8.
\[
R_0 = k'[C][S] + k''[C][A]_0 \\
[A]_0 = 0.05 - 1.25 \text{ M} \; [C] = 3.2 - 58 \text{ mM}
\]

(7)

In addition, product inhibition was observed; the reciprocal of the initial rate varies linearly as the initial concentration of the added enamine.

Fig. 2 Dependence of initial rates on substrate concentrations for isomerization of 7 catalyzed by \([\text{Rh}(\pm)-\text{binap})(\text{cod})]^+\) in THF-d\(_8\) at 60 °C.

Fig. 3 Dependence of initial rates on substrate concentrations for isomerization of 7 catalyzed by \([\text{Rh}(\pm)-\text{binap})(\text{MeOH})_2]^+\) in acetone-d\(_6\) at 27 °C.

Possible reaction mechanisms of the asymmetric 1,3-hydrogen migration and the reaction pathways

The observation that despite the different kinetic laws both the COD and methanol complex catalyzed isomerization gave comparable degrees of enantioselection with the same product stereochemistry suggests an identical stereochemical discrimination step. On the basis of the kinetic and NMR studies the isomerization may be accounted for by the reaction cycle described in Scheme 4. For the COD complex catalyzed isomerization dissociation of COD ligand would be the rate-determining step, whereas for the methanol complex catalyzed reaction release of the product from an enamine-rhodium complex \([\text{Rh}(\text{binap})(N-E)]^+\) (two parallel reactions, a solvent-assisted apparent unimolecular reaction and a second-order reaction, are possible) would be the rate-determining one. When the amount of the product increases, a path via bis(enamine) complex would become important. Neither of the reactions may be responsible for the enantio-discrimination. Enantioselection would be made at a stage somewhere in the course of transformation of \([\text{Rh}(\text{binap})(S)]^+\) to \([\text{Rh}(\text{binap})(N-E)]^+\), which is not kinetically important. This feature may be consistent with the observed unusual non-linear temperature dependence of the enantioselection.

\text{SCHEME 4}

\[
\begin{align*}
\text{[Rh(binap)(cod)]}^+ & \xrightarrow{S} \text{[Rh(binap)(S)]}^+ \xrightarrow{S} \text{[Rh(binap)(MeOH)]}^+ \\
\text{[Rh(binap)(N-E)]}^+ & \xrightarrow{S} \text{[Rh(binap)(N-A)(S)]}^+ \xrightarrow{E} \text{[Rh(binap)(N-E)]}^+ \xrightarrow{E} \text{[Rh(binap)(N-A)(S)]}^+ \\
A: \text{allylamine}; \quad E: \text{enamine}; \quad S: \text{solvent}
\end{align*}
\]
As one of the most plausible mechanisms for the observed stereospecific 1,3-hydrogen migration we consider the one described in Scheme 5. The rhodium-catalyzed isomerization starts with the formation of simple nitrogen coordinated rhodium complex \([\text{Rh(binap)(N-A)(S)})^+\] as shown in Scheme 4. Among possible several conformers of such \(N\)-allylamine rhodium complexes involved in the reaction of \((R)-18\) with binap rhodium complexes, the most stable one would be \(26\), where the allylamine has a conformation with the C(2)-C(3) double bond plane being gauche with \(\text{NEt}_2\) directing \(N\) lone-pair trans to C(2) and eclipsing one of the C(1) hydrogens (deuterium or protium) as expected from the theoretical calculation about simple allylamine (ref. 12) and the Rh-N bond is anti-periplanar to the C(2)-C(3) bond on steric ground. Although the two enantiomeric conformers of free geranylamine leading to \(26a\) and \(26b\) should be present in an equal population, the two complexes \(26a\) and \(26b\), formed by coordination of a chiral rhodium complex, become diastereomeric. In the complex \(26\) the deuterium and protium at C(1) can be differentiated (cf. the Newman projection of \(26a\) or \(26b\)) and the non-eclipsed, out-of-plane protium in case of \(26a\) is favorable for the metal hydride elimination by least motion leading to a rhodium-immonium complex \(27\) via a four-center transition state. Then the metal hydride species delivers the hydrogen atom to the C(3) position possibly via a \(\pi\)-allyl intermediate \(28\) to form the \((E)\)-enamine complex \(29\) possessing an aza-allyl type structure responsible for the eight-line signals in \(31^P\) NMR spectra, which ultimately give the free \((E, R)\)-enamine \((R)-9-1-d\) and the active rhodium catalyst. The transformation of \(26\) to \(29\) is facile as confirmed from \(31^P\) NMR and when \((S)-(\_)-\text{binap}\) complex is used, the course starting from the diastereomer \(26a\) would have the eminent preference.

\[
\text{SCHEME 5}
\]

\[
\begin{align*}
&\text{HC}=\text{CMeR}-(E) \\
&\text{Et} \\
&\text{R} \\
&\text{Et}
\end{align*}
\]

\[
\begin{align*}
&\equiv \text{MeD} \\
&\text{Et} \\
&\text{RhP}_2S
\end{align*}
\]

\[
\begin{align*}
&\equiv (E)-\text{RMeC}=\text{CH} \\
&\text{Et} \\
&\text{Et}
\end{align*}
\]

\[
\begin{align*}
&\text{P}_2\text{RhHS} \\
&\text{MeD} \\
&\text{NET}_2
\end{align*}
\]

\[
\begin{align*}
&\text{P}_2\text{RhH} \\
&\text{MeD} \\
&\text{NET}_2
\end{align*}
\]

\[
\begin{align*}
&\equiv \text{(E)}-\text{RMeC}=\text{CH} \\
&\text{Et} \\
&\text{Et}
\end{align*}
\]

\[
\begin{align*}
&R = (\text{CH}_3)_2\text{C}=\text{CHCH}_2\text{CH}_2 \\
&P_2 = (S)-(\_)-\text{BINAP} \\
&S = \text{solvent, substrate or product}
\end{align*}
\]

\[\text{N- Allylaziridine 30, where an immonium structure 31 is unfavorable (ref. 13), did not isomerize at all by [Rh(binap)(cod)]^+ in THF at 60 °C (eq. 8). This observation may be consistent with intermediacy of an immonium-rhodium complex in the catalytic cycle.}\]
CONCLUSION

A few salient features of the asymmetric isomerization of functionalized allylic compounds are summarized as follows: (1) excellent catalytic activity and selectivity of cationic rhodium complexes of the type \[ \text{[Rh(diphosphine)Me}_2 \text{]}^+ \], (2) per-aryldiphosphine, binap which has a C2 symmetry, is the best diphosphine ligand and allylamines are the best substrate; i) 100 % (E)-enamine formation, ii) >96 % ee, iii) the clear stereoelectronic correlation between the ligand, substrate, and product, (3) mechanistic aspects of the asymmetric isomerization of allylamine; i) 100 % stereospecific intramolecular 1,3-hydrogen migration probably via π-allyl mechanism, ii) a composite rate equation, iii) the enantioselection may be achieved at a step of kinetically unimportance, which contrasts with the catalytic asymmetric hydrogenation of acetaminocinnamate by rhodium(I) diphosphine complexes (ref. 14).

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REFERENCES

8. Takasago Perfumery Co. Ltd.