Asymmetric Catalysis of Planar-Chiral Cyclopentadienylruthenium Complexes in Allylic Amination and Alkylation

Yuji Matsushima,† Kiyotaka Onitsuka,† Teruyuki Kondo,‡ Take-aki Mitsudo,‡ and Shigetoshi Takahashi*,†

The Institute of Scientific and Industrial Research Osaka University, Ibaraki, Osaka 567-0047, Japan Department of Energy and Hydrocarbon Chemistry Graduate School of Engineering, Kyoto University Sakyo-ku, Kyoto 606-8501, Japan

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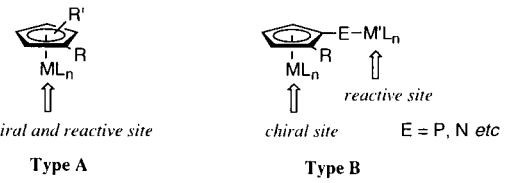
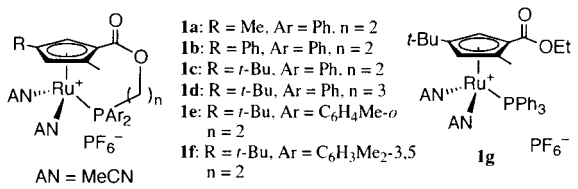
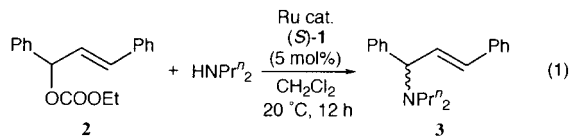
A great deal of effort has been directed toward the molecular design of chiral organometallic complexes, which are key to the development of transition metal-catalyzed asymmetric reactions.[1] Organometallic complexes bearing various chiral ligands such as chiral phosphines and amines are recognized as effective asymmetric catalysts.[2] In addition, increasing attention has been paid to other types of optically active complexes.[3,4] Planar-chiral complexes formed by π-coordination of prochiral unsaturated hydrocarbons fall in this latter category. The efficiency of planar chirality in asymmetric catalysis has been demonstrated by using early transition-metal complexes such as *ansa*-metallocenes.[5] There has been only one report, which showed low enantioselectivity, on the use of planar-chiral complexes of late transition metals as catalysts (type A).[6] Hayashi[7] and recently Fu[8] have studied asymmetric catalysis using planar-chiral ferrocene derivatives. In their system, metal species other than stable metal moieties that generate planar chirality, which simply serve as a bulky substituent, act as a reactive center of the catalyst (type B). Recently, we prepared novel planar-chiral cyclopentadienylruthenium complexes,[9] and found that ruthenium complexes (**1**) with an anchor phosphine ligand can control metal-centered chirality with high selectivity.[10] These results prompted us to develop a novel asymmetric reaction using complexes **1** as Type A catalyst.



Enantioselective allylic substitutions catalyzed by transition metal complexes provide a powerful method for constructing complex organic molecules.[11] Palladium-based catalysts have often given excellent results. To expand the scope of the reaction, however, extensive studies on alternative metal catalysts have been performed.[12] Although some ruthenium complexes show high catalytic activity for allylic substitutions,[13] an asymmetric version of such catalysis is still unknown. We describe here new enantioselective allylic amination and alkylation catalyzed by planar-chiral ruthenium complexes **1**.





Our initial experiments focused on the allylic amination with complex **1** as a catalyst. Representative results are shown in Table 1. Thus, the reaction of 1,3-diphenyl-2-propenyl ethyl carbonate (**2**) with 1.1 equiv of di-*n*-propylamine in the presence of 5 mol % of (*S*)-**1** proceeded smoothly at 20 °C to give the allylic aminated product (**3**) in a quantitative yield with 35% ee (Entry 1). Although the reaction with complex (*S*)-**1b** in place of (*S*)-**1a** gave similar results (90% yield, 20% ee), the product had a specific rotation with a sign opposite that obtained by (*S*)-**1a** (Entry 2). A bulkier substituent at the 4-position of the cyclopentadienyl ring increased the enantioselectivity to 64% ee (Entry 3), while a longer tether slightly decreased the enantioselectivity (Entry 4). The reaction catalyzed by **1g** which has no tether between the cyclopentadienyl and phosphine ligands, also proceeded with high enantioselectivity (Entry 7). The enantioselectivity was improved by using (*S*)-**1f** , which has 3,5-dimethylphenyl groups on the anchor phosphorus atom (Entry 6). In the

† Osaka University.
‡ Kyoto University.

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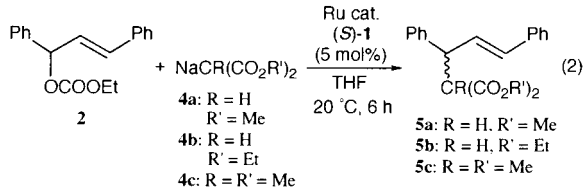
Table 1. Ruthenium-Catalyzed Asymmetric Allylic Amination

entry	catalyst	conversion (%)[a]	yield (%)[a,b]	ee (%)[c,d]
1	(*S*)-**1a**	100	97	35(−)
2	(*S*)-**1b**	98	90	20(+)
3	(*S*)-**1c**	100	99	64(+)
4	(*S*)-**1d**	100	94	56(+)
5	(*S*)-**1e**	100	93	57(+)
6	(*S*)-**1f**	100	98(89)	74(+)
7	(*S*)-**1g**	93	86	65(+)

[a] Conversion and yield were determined by HPLC on the basis of allyl carbonate (**2**). [b] The number in parentheses indicates an isolated yield. [c] The ee values were determined by HPLC equipped with a chiral column (Daicel Chiralcel OJ, hexane/*i*-PrOH/$HNEt_2$ 1000/1/1). [d] The sign of specific rotation of the products is given in parentheses.

reactions of Entries 3−7, the signs of the specific rotation of the products were the same as that of the product obtained with (*S*)-**1b**.

Since allylamines tend to react with ruthenium complexes to give π-allyl complexes, the possibility of the racemization of product **3** should be considered.[13b,14] A trace experiment of the reaction with (*S*)-**1f**, however, showed that the enantioselectivity stays constant independent of the conversion of **2**. When the reaction with (*S*)-**1f** was performed in the presence of an equimolar amount of racemic **3**, the enantioselectivity of the total product **3** was 34% ee, indicating that the enantioselectivity of the total product **3** was not affected by the addition of racemic **3**. These results clearly show that the **3** does not undergo racemization in the present reaction at all and that the enantioselectivity is determined by kinetic factors.



Ruthenium complexes **1** also catalyzed allylic alkylation with high enantioselectivity and high yields (Table 2). The reaction of allylic carbonate with sodium dimethyl malonate (**4a**) in the presence of 5 mol % of (*S*)-**1a** at 20 °C in THF resulted in the formation of the alkylated product (**5a**) in 96% yield with 80% ee (Entry 1). Although complexes (*S*)-**1b** and (*S*)-**1c** also showed high catalytic activity with excellent enantioselectivity to give **5a** (Entries 2 and 3), the absolute configuration of the product **5a** was opposite that obtained by (*S*)-**1a**, as noted above for the amination. The tether dramatically affects not only the enantioselectivity of the product but also the reactivity of the catalyst. Thus, the reaction with (*S*)-**1d** afforded **5a** in 14% yield with 10% ee (Entry 4), while complex (*S*)-**1g** hardly catalyzed the allylic alkylation at all (Entry 7). In contrast to amination, the substituents on the aromatic rings on the anchor phosphine had little influence on the enantioselectivity in alkylation (Entries 5 and 6). When sodium diethyl malonate (**4b**) was used as a

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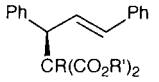
Table 2. Ruthenium-Catalyzed Asymmetric Allylic Alkylation

entry	catalyst	nucleophile	conversion (%)[a]	product	yield (%)[a,b]	ee (%)[c,d]
1	(*S*)-**1a**	**4a**	98	**5a**	96	80(*R*)
2	(*S*)-**1b**	**4a**	97	**5a**	91	91(*S*)
3	(*S*)-**1c**	**4a**	99	**5a**	97	96(*S*)
4	(*S*)-**1d**	**4a**	19	**5a**	14	10(*S*)
5	(*S*)-**1e**	**4a**	100	**5a**	98	97(*S*)
6	(*S*)-**1f**	**4a**	100	**5a**	99(79)	96(*S*)
7	(*S*)-**1g**	**4a**	10	**5a**	3	
8	(*S*)-**1a**	**4b**	100	**5b**	96(88)	94(*R*)
9	(*S*)-**1f**	**4b**	87	**5b**	85(77)	96(*S*)
10	(*S*)-**1a**	**4c**	91	**5c**	82	63(*S*)
11	(*S*)-**1c**	**4c**	88	**5c**	75	82(*R*)
12	(*S*)-**1f**	**4c**	88	**5c**	80(68)	83(*R*)

[a] Conversion and yield were determined by HPLC on the basis of allyl carbonate (**2**). [b] The number in parentheses indicates an isolated yield. [c] The ee values were determined by HPLC equipped with a chiral column (**5a**, Daicel Chiralcel OD, hexane/*i*-PrOH 99/1; **5b**, Daicel Chiralcel OJ, hexane/*i*-PrOH 19/1) and/or by ^{1}H NMR spectroscopy using a chiral shift reagent Eu(hfc)$_3$ in $CDCl_3$. [d] Configuration of the products was assigned on the basis of the sign of specific rotation according to the literature (**5a**, ref 15; **5b**, see Supporting Information; **5c**, ref 16).



(*S*)-**5a**: R = H, R' = Me
(*S*)-**5b**: R = H, R' = Et
(*R*)-**5c**: R = R' = Me

nucleophile, approximately the same results were obtained (Entries 8 and 9). However, the reaction with sodium dimethyl methylmalonate (**4c**) led to a slight decrease in both yield and enantioselectivity relative to those with **4a** (Entries 10−12). In all cases, the configuration of the products with (*S*)-**1a** was opposite those obtained with other complexes, indicating that the substituents at the 4-position of the cyclopentadienyl ring play an extremely important role in controlling stereochemistry in the present reactions.

In summary, we have developed asymmetric allylic substitutions catalyzed by planar-chiral cyclopentadienyl-ruthenium complexes, in which we achieved enantioselectivities of up to 74% ee for amination and 97% ee for alkylation. To the best of our knowledge, this is not only the first successful ruthenium-catalyzed asymmetric allylic amination and alkylation, it is also the first asymmetric catalysis of planar-chiral complexes of late transition metals. Further studies on the reaction mechanism to understand the origin of the enantioselectivity and on the application of planar-chiral ruthenium catalysts to other asymmetric reactions are in progress.

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Supporting Information Available: Experimental details, spectroscopic data for complexes **1d**−**1f**, and characterization of 1,3-diphenyl-2-propenyl-di-*n*-propylamine (**4**) (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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