JOC Article

Direct Preparation of Allylic Zirconium Reagents from Zirconocene−Olefin Complexes and Alkenes

Kazuya Fujita, Hideki Yorimitsu, Hiroshi Shinokubo, and Koichiro Oshima*

Department of Material Chemistry, Graduate School of Engineering, Kyoto University, Kyoto-daigaku Katsura, Nishikyo-ku, Kyoto 615-8510, Japan

oshima@fm1.kuic.kyoto-u.ac.jp

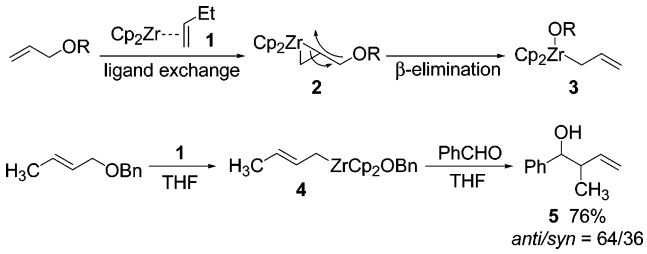
Received January 23, 2004

A novel method for preparation of allylic zirconium reagents directly from 1-alkenes via zirconocene−olefin complex has been developed. Selective transfer of the hydride of zirconocene allyl hydride complex, a tautomer of zirconocene−olefin complex, to diisopropyl ketone generates the corresponding zirconocene alkoxide allyl. The allylic zirconium reagents formed effects stereoselective allylation of aldehyde at 25 °C and −78 °C to provide *syn*- and *anti*-homoallyl alcohols, respectively. The *anti*-isomer is formed via a six-membered chair transition state under kinetic control. The *syn*-selectivity can be rationalized by considering isomerization of the *anti*-adduct by a retroallylation process.

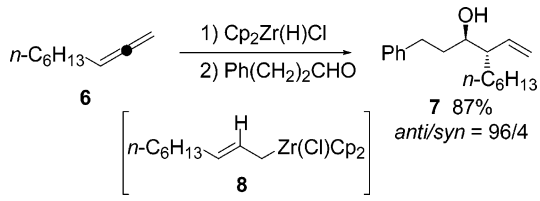
Introduction

Allylation of carbonyl groups by allylic metals is one of the most versatile C−C bond formation reactions.[1] Although there are a number of precedents for the synthesis of allylic metals, the preparation usually requires alkenes that have good leaving groups such as alkoxide or halide at the allylic position. As far as zirconium compounds are concerned,[2] Taguchi and Hanzawa reported efficient preparation of allylic zirconium species through reaction of zirconocene−olefin complex $Cp_2Zr(H_2C{=}CHEt)$ with allylic ether by taking advantage of the high oxophilicity of zirconium metal (Scheme 1).[3] This transformation was achieved through the formation of zirconacyclopropane **2** (ligand exchange) followed by elimination of the β-alkoxy group. The allylic zirconium reagent **4** prepared in a similar way reacted with aldehyde in a regio- and diastereoselective manner to afford the homoallylic alcohol. Suzuki demonstrated that hydrozirconation of allenes provided a useful method for the generation of various allylic zirconocene derivatives, for example, **8** (Scheme 2).[4]

SCHEME 1



SCHEME 2



However, preparation of requisite allyl ethers or allenes is still laborious. A novel method for preparation of allylic zirconium reagents from readily available 1-alkenes would greatly enhance the synthetic utility of allylic zirconium reagents. Recently, we have found zirconocene−olefin complex **1** delivers both hydride and an allyl group to acid chloride to furnish homoallyl alcohol **10** (Scheme 3).[5] It is assumed that an equilibrium exists between **1** and **9**.[6] We then anticipated that selective capture of hydride in zirconocene allyl hydride complex **9** with a bulky ketone would provide a new

* To whom correspondence should be addressed. Phone: +81-75-383-2437. Fax: +81-75-383-2438.

(1) (a) Roush, W. R. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford 1991; Vol. 2, Chapter 1.1. (b) Yamamoto, Y.; Asao, N. *Chem. Rev.* **1993**, *93*, 2207.

(2) Preparation of allylic zirconium compounds has also been achieved by transmetalation of allylmetal with Cp_2ZrCl_2. (a) Yamamoto, Y.; Maruyama, K. *Tetrahedron Lett.* **1981**, *22*, 2895. (b) Yasuda, H.; Kajihara, Y.; Mashima, K.; Nagasuna, K.; Nakamura, A. *Chem. Lett.* **1981**, 671. (c) Mashima, K.; Asami, K.; Yasuda, H.; Nakamura, A. *Chem. Lett.* **1983**, 219.

(3) (a) Ito, H.; Taguchi, T.; Hanzawa, Y. *Tetrahedron Lett.* **1992**, *33*, 1295. (b) Ito, H.; Nakamura, T.; Taguchi, T.; Hanzawa, Y. *Tetrahedron* **1995**, *51*, 4507. (c) Hanzawa, Y.; Ito, H.; Taguchi, T. *Synlett* **1995**, 299. Their allyl zirconium afforded *anti*-homoallylic alcohols even at ambient temperature upon treatment with aldehydes. Also see: (d) Rousset, C. J.; Swanson, D. R.; Lamaty, F.; Negishi, E. *Tetrahedron Lett.* **1989**, *30*, 5105.

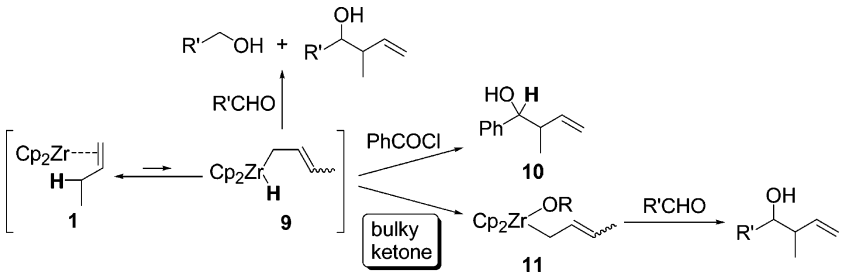
(4) Chino, M.; Matsumoto, T.; Suzuki, K. *Synlett* **1994**, 359.

(5) (a) Fujita, K.; Yorimitsu, H.; Shinokubo, H.; Oshima, K. *J. Am. Chem. Soc.* **2001**, *123*, 12115. (b) Fujita, K.; Shinokubo, H.; Oshima, K. *Angew. Chem., Int. Ed.* **2003**, *42*, 2550. (c) Fujita, K.; Yorimitsu, H.; Oshima, K. *Chem. Rec.* **2004**, *4*, 110.

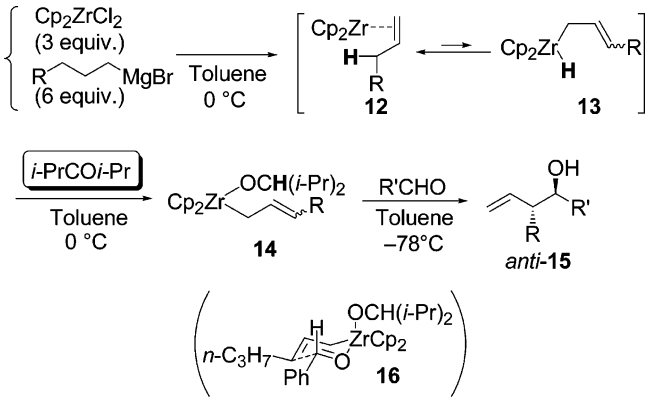
(6) Harrod has also proved that **1** and **9** are in an equilibrium that is significantly shifted toward **1**: Dioumaev, V. K.; Harrod, J. F. *Organometallics* **1997**, *16*, 1452. Also see: Negishi, E.; Maya, J. P.; Choueiry, D. *Tetrahedron* **1995**, *51*, 4447.

10.1021/jo049863r CCC: $27.50 © 2004 American Chemical Society
Published on Web 04/14/2004

SCHEME 3



SCHEME 4



allylzirconium reagent **11**. When **9** reacted with aldehyde, attacks of the hydride and allyl group competed to afford a mixture of the parent primary alcohol and the corresponding homoallylic alcohol. In contrast, the reaction of **11** with aldehyde never suffers from the competitive nucleophilic attack. Here, we describe a novel method to prepare versatile allylic zirconium reagents directly from 1-alkenes.

Results and Discussion

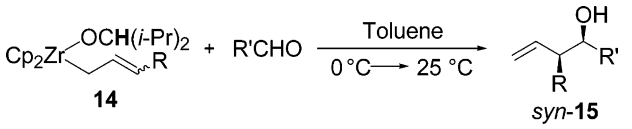
Treatment of Cp_2ZrCl_2 (3.0 mmol) with *n*-$C_6H_{13}MgBr$ (1.0 M THF solution, 6.0 mL, 6.0 mmol) in toluene (30 mL) at 0 °C provided zirconocene complex **12a** (R = *n*-C_3H_7).[7,8] After 30 min of stirring at 0 °C, an addition of diisopropyl ketone (4.5 mmol) to the solution at the same temperature resulted in reduction of the ketone and afforded allylzirconium **14a** (R = *n*-C_3H_7) in situ. Reaction with benzaldehyde (1.0 mmol) at −78 °C for 5 h yielded homoallyl alcohol **15a** in 98% yield with a high level of *anti* stereoselectivity (Scheme 4). Use of 2.0 equiv of allylzirconium provided **15a** in only 60% yield along with the recovered benzaldehyde. In this method, the employment of diisopropyl ketone as a hydrogen scavenger is crucial for the successful formation of allylzirconium reagent. For instance, the use of a ketone without steric hindrance, such as acetone or 2-pentanone, instead of diisopropyl ketone decreased the yield of **15a**, and a significant amount of benzyl alcohol was obtained. Other results are shown in Table 1 (Method A). The use of butylmagnesium bromide and 3-phenylpropylmagnesium bromide in place of *n*-$C_6H_{13}MgBr$ also provided the corresponding homoallylic alcohols (Table 1, entries 5−8). Decanal or cyclohexanecarbaldehyde also yielded the desired homoallylic alcohols.[9,10] Most of the reactions accomplished satisfactory yields with good to excellent *anti* stereoselectivity. In all cases, none of the regioisomer, linear α-adduct, was detected. A six-membered chairlike transition state **16** can explain the regio- and diastereoselectivity.[2,5a]

TABLE 1. Reaction of Allylic Zirconium Reagents with Aldehydes

entry	method[a]	R	R′	product	yield (%)	*anti*/*syn*
1	**A**	*n*-C_3H_7	Ph	**15a**	98	91/9
2	**A**	*n*-C_3H_7	*n*-C_9H_{19}	**15b**	94	>99/1
3	**A**	*n*-C_3H_7	*c*-C_6H_{11}	**15c**	99	94/6
4	**A**	*n*-C_3H_7	$Ph(CH_2)_3$	**15d**	97	93/7
5	**A**	CH_3	Ph	**15e**	98	68/32
6	**A**	CH_3	*n*-C_9H_{19}	**15f**	85	86/14
7	**A**	CH_3	PhCH=CH	**15g**	80	77/23
8	**A**	Ph	Ph	**15h**	95	95/5
9	**B**	*n*-C_3H_7	Ph	**15a**	98	23/77
10	**B**	*n*-C_3H_7	*n*-C_9H_{19}	**15b**	91	43/57
11	**B**	*n*-C_3H_7	*c*-C_6H_{11}	**15c**	95	17/83
12	**B**	*n*-C_3H_7	$Ph(CH_2)_3$	**15d**	94	15/85
13	**B**	CH_3	Ph	**15e**	99	35/65
14	**B**	CH_3	*n*-C_9H_{19}	**15f**	99	26/74
15	**B**	CH_3	PhCH=CH	**15g**	95	14/86
16	**B**	Ph	Ph	**15h**	99	25/75

[a] Reaction conditions. Method A: Cp_2ZrCl_2 (3.0 mmol), Grignard reagent (1.0 M in THF, 6.0 mL, 6.0 mmol), diisopropyl ketone (4.5 mmol), aldehyde (1.0 mmol), and toluene (30 mL) were employed at −78 °C. Method B: Cp_2ZrCl_2 (2.0 mmol), Grignard reagent (1.0 M in THF, 4.0 mL, 4.0 mmol), diisopropyl ketone (3.0 mmol), aldehyde (1.0 mmol), and toluene (20 mL) were employed at 25 °C.

SCHEME 5



To our surprise, warming up the reaction mixture before aqueous workup reversed the sense of the diastereoselectivity (Scheme 5). Thus, the reaction of allylzirconium reagent **14a** (R = *n*-C_3H_7) with decanal at ambient temperature furnished homoallyl alcohol in

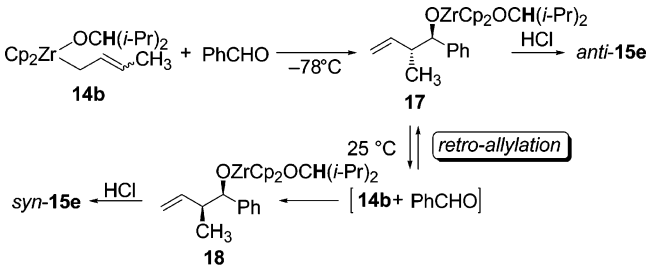
(7) (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (b) Negishi, E.; Holms, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336.

(8) For leading reviews, see: (a) Negishi, E.; Takahashi, T. *Acc. Chem. Res.* **1994**, *27*, 124. (b) Negishi, E.; Kondakov, D. Y. *Chem. Soc. Rev.* **1996**, *26*, 417. (c) Negishi, E.; Takahashi, T. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 755. (d) Takahashi, T.; Kotora, M.; Hara, R.; Xi, Z. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 2591.

(9) The reaction with acetophenone yielded the allylation product in only 19% yield.

(10) The reaction with pivalaldehyde led to the sole production of the *syn* isomer regardless of the reaction temperatures.

SCHEME 6



quantitative yield with *syn* selectivity (*anti*/*syn* = 23/77). A range of aldehydes and Grignard reagents were screened (Table 1, Method B). In all cases, the reaction exhibited high *syn* selectivity with excellent yields of the desired products.

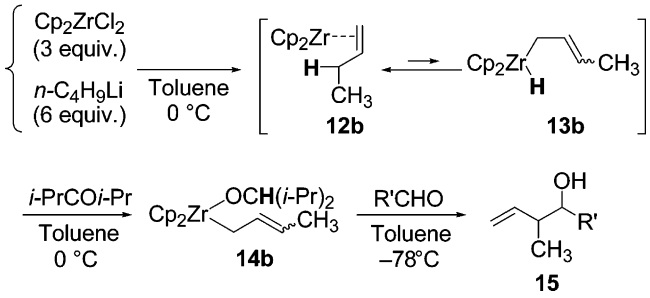
To elucidate the reaction pathway, we carried out the following experiment (Scheme 6). Crotylzirconium **14b** (R = CH_3) was treated with benzaldehyde at −78 °C for 5 h. A small portion of the reaction mixture was taken out by a syringe and hydrolyzed. The stereochemistry of the major product was *anti* (*anti*/*syn* = 72/28), and benzaldehyde was not detected in the reaction mixture. The remaining mixture was then warmed to room temperature. Protonolysis afforded the *syn* isomer as a main product (*anti*/*syn* = 26/74).

On the basis of these facts, we are tempted to propose that the fact that the stereoselectivity depended on the reaction temperature is attributed to isomerization of the product via a retroallylation reaction. The *anti*-zirconium alkoxide **17** is formed predominantly under kinetic control at −78 °C. At ambient temperature, however, **17** undergoes the retroallylation reaction affording crotyl zirconium reagent and benzaldehyde. Finally, the reaction provides *syn*-alkoxide **18** as a major product. The result indicates that *syn*-alkoxide **18** would be thermodynamically more stable than *anti*-adduct **17**. Knochel et al. reported that generation of a zinc alkoxide of a sterically hindered tertiary homoallyl alcohol would result in decomposition to the parent ketone and an allylic zinc reagent.[11] On the other hand, we have demonstrated the first example of a reversible addition process of allylic metals to aldehyde.

We also conducted the following experiment to establish the mechanism involving the retroallylation reaction (Scheme 7). Crotylzirconium **14b** (2.0 mmol) was treated with cyclohexanecarbaldehyde (2.4 mmol) at −78 °C for 5 h. Quenching of the reaction mixture with aqueous hydrochloric acid yielded 1.4 mmol of 1-cyclohexyl-2-methyl-3-buten-1-ol (**20**). Thus, zirconium alkoxide **19** was formed in situ at this point. Before quenching, addition of benzaldehyde (2.4 mmol) to **19** at −78 °C followed by warming up the reaction temperature afforded *syn*-adduct **15e** exclusively (1.4 mmol) with contamination by *syn*-**20**. The result proves that zirconium alkoxide **19** fragmented to furnish crotylzirconium reagent **14b** and that allylation of aldehyde with **14b** is thus reversible.

(11) (a) Jones, P.; Millot, N.; Knochel, P. *Chem. Commun.* **1998**, 2405. (b) Jones, P.; Knochel, P. *Chem. Commun.* **1998**, 2407. (c) Millot, N.; Knochel, P. *Tetrahedron Lett.* **1999**, *40*, 7779. (d) Jones, P.; Knochel, P. *J. Org. Chem.* **1999**, *64*, 186. In their reaction system, the employment of a sterically hindered tertiary allylic alcohol is crucial for the successful formation of allylzinc species.

TABLE 2. Reaction of Crotylzirconium Reagent, Derived from Cp_2ZrCl_2 and *n*-C_4H_9Li, with Aldehydes



entry	method[a]	R′	product	yield (%)	*anti*/*syn*
1	**A**	Ph	**15e**	66	84/16
2	**A**	*n*-C_9H_{19}	**15f**	72	91/9
3	**A**	PhCH=CH	**15g**	69	88/12
4	**B**	Ph	**15e**	81	41/59
5	**B**	*n*-C_9H_{19}	**15f**	84	47/53
6	**B**	PhCH=CH	**15g**	82	49/51

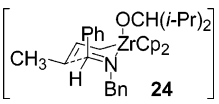
[a] Reaction conditions. Method A: Cp_2ZrCl_2 (3.0 mmol), *n*-C_4H_9Li (1.6 M in hexane, 3.75 mL, 6.0 mmol), diisopropyl ketone (4.5 mmol), aldehyde (1.0 mmol), and toluene (30 mL) were employed at −78 °C. Method B: Cp_2ZrCl_2 (2.0 mmol), *n*-C_4H_9Li (1.6 M in hexane, 2.5 mL, 4.0 mmol), diisopropyl ketone (3.0 mmol), aldehyde (1.0 mmol), and toluene (20 mL) were employed at 25 °C.

The reaction also worked well with *n*-C_4H_9Li instead of *n*-C_4H_9MgBr. Additionally, it was found that the use of *n*-C_4H_9Li influences the stereochemical outcome of the reaction. The results are summarized in Table 2. When the reaction was conducted with *n*-C_4H_9Li at −78 °C, the stereoselectivity was improved compared to the case of *n*-C_4H_9MgBr (entries 1−3). On the other hand, the reaction at 25 °C lacked the stereoselectivity (entries 4−6). We assume that the metal halide, which was formed by transmetalation, plays an important role.

The reaction could employ imines as an electrophile and afforded homoallylamines. The addition to aldimines **21** provided the corresponding secondary amines **22** in good to excellent yields. Interestingly, in the reaction with imines, *syn*-homoallylic amines were obtained predominantly regardless of the reaction temperatures (Table 3).[12]

Zirconocene−olefin complexes can also be prepared from 1-alkenes directly upon treatment with zirconocene−cyclopentene complex **23** derived from Cp_2ZrCl_2 and cyclopentylmagnesium bromide (Scheme 8).[13] The zirconium reagent prepared in this manner could effect allylation of carbonyl compounds. Thus, an addition of diisopropyl ketone followed by various aldehydes yielded the corresponding homoallyl alcohols (Table 4).[14]

(12) The *syn* selectivity can be explained by six-membered chairlike transition state **24**. See: (a) Yamamoto, Y.; Nishi, S.; Maruyama, K.; Komatsu, T.; Ito, W. *J. Am. Chem. Soc.* **1986**, *108*, 7778. (b) Gao, Y.; Sato, F. *J. Org. Chem.* **1995**, *60*, 8136.



(13) A similar ligand exchange utilizing a titanium reagent was reported: (a) Lee, J.; Kim, H.; Cha, J. K. *J. Am. Chem. Soc.* **1995**, *117*, 9919. (b) Lee, J.; Kim, H.; Cha, J. K. *J. Am. Chem. Soc.* **1996**, *118*, 4198. (c) Kulinkovich, O. G.; de Meijere, A. *Chem. Rev.* **2000**, *100*, 2789. (d) Sato, F.; Urabe, H.; Okamoto, S. *Chem. Rev.* **2000**, *100*, 2835. Also see ref 5a.

SCHEME 7

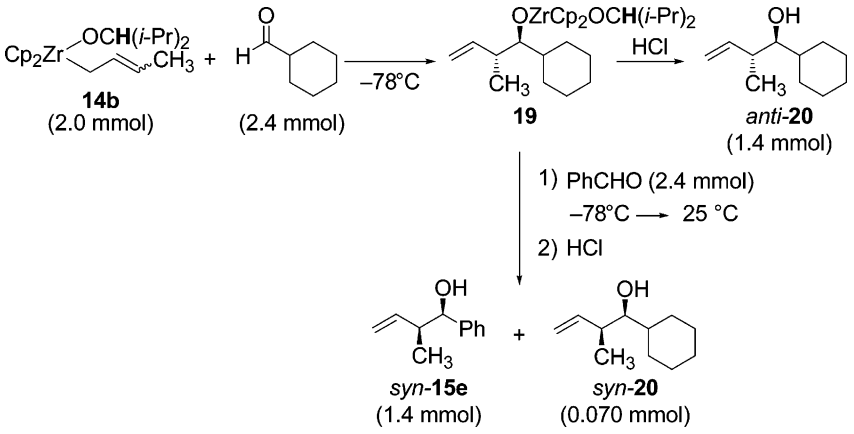
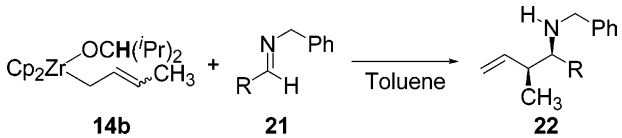


TABLE 3. Reaction of Crotylzirconium Reagent with Imines



entry	method[a]	R	product	yield (%)	*anti*/*syn*
1	**A**	Ph	**22a**	67	11/89
2	**A**	*i*-C_3H_7	**22b**	73	17/83
3	**A**	*c*-C_6H_{11}	**22c**	69	18/82
4	**B**	Ph	**22a**	87	25/75
5	**B**	*i*-C_3H_7	**22b**	87	22/78
6	**B**	*c*-C_6H_{11}	**22c**	74	22/78

[a] Reaction conditions. Method A: Cp_2ZrCl_2 (3.0 mmol), butylmagnesium bromide (1.0 M in THF, 6.0 mL, 6.0 mmol), diisopropyl ketone (4.5 mmol), aldimine (1.0 mmol), and toluene (30 mL) were employed at −78 °C. Method B: Cp_2ZrCl_2 (2.0 mmol), butylmagnesium bromide (1.0 M in THF, 4.0 mL, 4.0 mmol), diisopropyl ketone (3.0 mmol), aldimine (1.0 mmol), and toluene (20 mL) were employed at 25 °C.

TABLE 4. Preparation of Allylic Zirconium Reagent from Alkenes

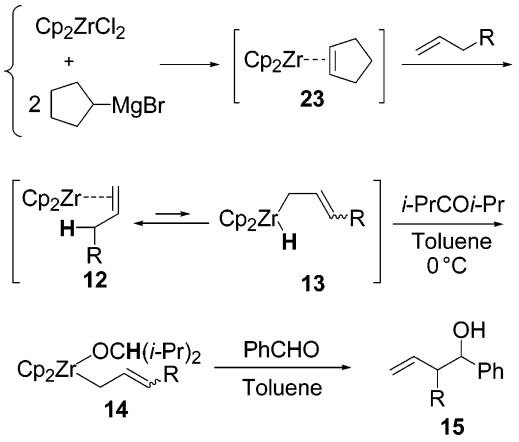
entry	method[a]	R	product	yield (%)	*anti*/*syn*
1	**A**	C_2H_5	**15i**	83	81/19
2	**A**	*n*-C_3H_7	**15a**	82	89/11
3	**A**	*n*-C_5H_{11}	**15j**	64	89/11
4	**A**	Ph	**15h**	76	96/4
5	**B**	C_2H_5	**15i**	93	26/74
6	**B**	*n*-C_3H_7	**15a**	85	23/77
7	**B**	*n*-C_5H_{11}	**15j**	72	28/72
8	**B**	Ph	**15h**	60	13/87

[a] Reaction conditions. Method A: Cp_2ZrCl_2 (3.0 mmol), cyclopentylmagnesium bromide (1.0 M in THF, 6.0 mL, 6.0 mmol), diisopropyl ketone (4.5 mmol), aldehyde (1.0 mmol), and toluene (30 mL) were employed at −78 °C. Method B: Cp_2ZrCl_2 (2.0 mmol), cyclopentylmagnesium bromide (1.0 M in THF, 4.0 mL, 4.0 mmol), diisopropyl ketone (3.0 mmol), aldehyde (1.0 mmol), and toluene (20 mL) were employed at 25 °C.

Conclusion

In summary, we have developed a novel protocol to prepare an allylzirconium reagent from alkene. The present method involves formation of a zirconocene−olefin complex, allylic C−H bond activation of the alkene on zirconium to form zirconocene allyl hydride complex, and selective removal of the hydride by transferring the hydride to diisopropyl ketone. In general, direct formation of allylic metals from alkenes employs highly basic and nucleophilic organolithium reagent.[15] Thus, the easy accessiblility to allylic zirconocene and its moderate reactivity is beneficial in organic synthesis. In addition, we have revealed that changing the reaction temperature from −78 to 25 °C can switch the sense of stereoselectivity of the products. Our study of this thermodynamic conversion proposes a retroallylation reaction to generate the parent aldehyde and allylic zirconocene.

SCHEME 8



Experimental Section

Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Tetrahydrofuran (THF) was freshly distilled from sodium benzophenone ketyl before use. Toluene was dried over slices of sodium.

General Procedure for Reaction of Allylic Zirconium Reagents with Aldehydes at −78 °C (Method A). Toluene (30 mL) and Cp_2ZrCl_2 (878 mg, 3.0 mmol) were placed in a reaction flask under argon. After the mixture was cooled to 0

(14) Reduction of Cp_2ZrCl_2 with Mg metal in the presence of an alkene also furnishes zirconium−olefin complex. However, in this procedure, pinacol coupling of an aldehyde predominates to yield hydrobenzoin without formation of the desired homoallyl alcohol. See ref 5a.

(15) From a simple alkene: (a) Heus-Kloos, Y. A.; de Jong, R. L. P.; Verkruijsse, H. D.; Brandsma, L.; Julia, S. *Synthesis* **1985**, 958. (b) Akiyama, S.; Hooz, J. *Tetrahedron Lett.* **1973**, *14*, 4115. From an alkene having a metal directing group: (c) Hoppe, D.; Hense, T. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2282. (d) Prasad, K. R. K.; Hoppe, D. *Synlett* **2000**, 1067. (e) Pippel, D. J.; Weisenberger, G. A.; Faibish, N. C.; Beak, P. *J. Am. Chem. Soc.* **2001**, *123*, 4919.

°C in an ice−water bath, hexylmagnesium bromide (6.0 mL, 1.0 M THF solution, 6.0 mmol) was added dropwise. The solution immediately became a viscous black suspension, and the resulting mixture was stirred for 30 min at 0 °C. A solution of diisopropyl ketone (515 mg, 4.5 mmol) in toluene (2 mL) was added at 0 °C, and the mixture was stirred for 3 h at 0 °C. A solution of benzaldehyde (106 mg, 1.0 mmol) in toluene was added dropwise to the reaction mixture at −78 °C. After stirring for another 5 h at the same temperature, the mixture was poured into aqueous HCl (50 mL, 3 M) and extracted with hexane/ethyl acetate. The combined organic layer was dried over Na_2SO_4 and concentrated in vacuo. The crude oil was purified on silica gel to yield 2-ethenyl-1-phenyl-1-pentanol (**15a**, 186 mg, 0.98 mmol) in 98% yield.

Typical Procedure Using Allylic Zirconium Reagents with Aldehydes at 25 °C (Method B). Hexylmagnesium bromide (4.0 mL, 1.0 M THF solution, 4.0 mmol) was added dropwise to a solution of Cp_2ZrCl_2 (585 mg, 2.0 mmol) in toluene (20 mL) at 0 °C, and the mixture was stirred at the same temperature for 30 min. To the reaction mixture was added a solution of diisopropyl ketone (343 mg, 3.0 mmol) in toluene (2 mL) at 0 °C. After 3 h of stirring at 0 °C, benzaldehyde (106 mg, 1.0 mmol) was added at 0 °C, and the mixture was stirred at 25 °C for 5 h. The mixture was poured into aqueous hydrochloric acid (50 mL, 3 M). Extraction with hexane/ethyl acetate followed by silica gel column purification afforded 2-ethenyl-1-phenyl-1-pentanol (**15a**, 186 mg, 0.98 mmol) in 98% yield.

General Procedure for Synthesis of Homoallylic Amines with Allylic Zirconium Reagents. Toluene (30 mL) was added to Cp_2ZrCl_2 (878 mg, 3.0 mmol) in a flask under argon. After the mixture was cooled to 0 °C in an ice−water bath, butylmagnesium bromide (6.0 mL, 1.0 M THF solution, 6.0 mmol) was added, and the resulting mixture was stirred for 30 min 0 °C. A solution of diisopropyl ketone (515 mg, 4.5 mmol) in toluene (2 mL) was added at 0 °C, and the mixture was stirred at the same temperature for 3 h. *N*-Benzylideneben-zylamine (195 mg, 1.0 mmol) was added at 0 °C, and the mixture was stirred for another 5 h at −78 °C. Quenching the reaction with aqueous hydrochloric acid followed by extraction, concentration, and silica gel column purification provided *N*-phenylmethyl-2-methyl-1-phenyl-3-buten-1-amine (**22a**, 168 mg, 0.67 mmol) in 67% yield as a colorless oil.

Typical Procedure via Olefin Exchange. Cyclopentyl-magnesium bromide (6.0 mL, 1.0 M THF solution, 6.0 mmol) was added to a solution of Cp_2ZrCl_2 (878 mg, 3.0 mmol) and 1-pentene (631 mg, 9.0 mmol) in toluene (30 mL) at 0 °C. The reaction mixture was stirred for 30 min at 0 °C and then for an additional 1 h at 25 °C. Next, the resulting mixture was cooled to 0 °C again, diisopropyl ketone (515 mg, 4.5 mmol) was added, and the resulting mixture was stirred for 3 h at 25 °C. After the solution was cooled to −78 °C, a solution of benzaldehyde (106 mg, 1.0 mmol) was added. The mixture was stirred for another 5 h at −78 °C and poured into aqueous hydrochloric acid (50 mL, 3 M). Extraction with hexane/ethyl acetate followed by silica gel column purification afforded 2-ethenyl-1-phenyl-1-butanol (**15i**, 158 mg, 0.83 mmol) in 83% yield.

Characterization Data. Spectral data for several compounds (**15a**, **15c**, **15e**, **15f**, **15h**, **15i**, **15j,** and **20**) were found in the literatures.[5a,16,17] Identification of *syn* and *anti* isomers of new compounds was carried out by comparing their ^{1}H NMR spectra with known compounds such as **15e**. The *syn*/*anti* ratios were determined by ^{1}H NMR.

3-Propyl-1-tridecen-4-ol (15b, mixture of stereoisomers, *anti*/*syn* = 94/6): IR (neat) 3379, 3074, 2926, 2855, 1638, 1466, 1421, 1379, 1001, 912, 721 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.88 (t, J = 6.6 Hz, 3H), 0.90 (t, J = 6.9 Hz, 3H), 1.20−1.53 (m, 20H), 1.53 (bs, 1H), 1.96−2.08 (m, 1H), 3.45 (ddd, J = 3.6, 5.4, 9.0 Hz, 1H), 5.08 (dd, J = 2.1, 17.1 Hz, 1H), 5.17 (dd, J = 2.1, 10.2 Hz, 1H) 5.64 (ddd, J = 9.3, 10.2, 17.1 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 14.2, 14.2, 20.6, 22.8, 25.8, 29.4, 29.7, 29.7, 29.8, 32.0, 33.1, 34.8, 50.1, 73.6, 117.6, 138.9. Anal. Calcd for $C_{16}H_{32}O$: C, 79.93; H, 13.41. Found: C, 79.65; H, 13.15.

1-Phenyl-2-propyl-3-buten-1-ol (*anti*-15d, mixture of isomers, *anti*/*syn* = 96/4; *syn*-15d, mixture of isomers, *anti*/*syn* = 15/85): IR (neat) 3412, 3065, 3026, 2930, 2872, 1724, 1638, 1603, 1497, 1454, 1032, 1001, 914, 748, 700 cm^{-1}; ^{1}H NMR ($CDCl_3$) for *anti* adduct δ 0.80 (t, J = 6.9 Hz, 3H), 1.06−1.44 (m, 4H), 1.57 (bs, 1H), 1.58−1.82 (m, 2H), 1.90−2.02 (m, 1H), 2.52−2.91 (m, 2H), 3.39 (ddd, J = 3.6, 3.6, 7.2 Hz, 1H), 5.02 (dd, J = 2.1, 17.4 Hz, 1H), 5.10 (dd, J = 2.1, 10.2 Hz, 1H), 5.55 (ddd, J = 9.3, 10.2, 17.4 Hz, 1H), 7.06−7.24 (m, 5H); for *syn* adduct δ 0.78 (t, J = 7.2 Hz, 3H), 1.03−1.43 (m, 4H), 1.49 (bs, 1H), 1.52−1.74 (m, 2H), 1.87−2.00 (m, 1H), 2.45−2.84 (m, 2H), 3.30 (ddd, J = 3.3, 3.6, 6.9 Hz, 1H), 4.94 (dd, J = 1.8, 16.8 Hz, 1H), 5.02 (dd, J = 1.8, 10.2 Hz, 1H), 5.45 (ddd, J = 9.0, 10.2, 16.8 Hz, 1H), 7.04−7.22 (m, 5H); ^{13}C NMR ($CDCl_3$) for *anti* adduct δ 14.1, 20.5, 32.2, 32.9, 36.6, 50.3, 73.0, 117.9, 125.6, 128.2, 128.3, 138.6, 142.2; for *syn* adduct δ 14.2, 20.5, 32.1, 32.8, 36.6, 47.3, 73.0, 117.9, 125.9, 128.2, 128.5, 138.6, 142.2. Anal. Calcd for $C_{15}H_{22}O$: C, 82.66; H, 10.35. Found: C, 82.52; H, 10.16.

4-Methyl-1-phenyl-1,5-hexadien-3-ol (15g, mixture of stereoisomers, *anti*/*syn* = 77/23): IR (neat) 3400, 3061, 3026, 2974, 2872, 1639, 1495, 1450, 966, 916, 750, 692 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.04 (d, J = 6.9 Hz, 2.31H), 1.07 (d, J = 7.5 Hz, 0.69H), 2.01 (bs, 0.23H), 2.09 (bs, 0.77H), 2.28−2.40 (m, 0.77H), 2.38−2.51 (m, 0.23H), 4.03 (dd, J = 6.9, 6.9 Hz, 0.77H), 4.17 (dd, J = 6.6, 6.6 Hz, 0.23H), 5.14 (dd, J = 1.8, 9.3 Hz, 1H), 5.16 (dd, J = 1.8, 18.3 Hz, 1H), 5.80 (ddd, J = 7.8, 9.3, 18.3 Hz, 0.77H), 5.82 (ddd, J = 7.8, 9.3, 18.3 Hz, 0.23H), 6.19 (dd, J = 6.9, 15.6 Hz, 0.77H), 6.20 (dd, J = 6.6, 15.6 Hz, 0.23H), 6.56 (d, J = 15.6 Hz, 0.23H), 6.58 (d, J = 15.6 Hz, 0.77H), 7.18−7.41 (m, 5H); ^{13}C NMR ($CDCl_3$) for major isomer δ 16.0, 44.6, 76.1, 116.4, 126.3, 127.5, 128.4, 130.1, 131.5, 136.6, 140.0; for minor isomer δ 14.9, 43.9, 75.7, 115.8, 126.3, 127.4, 128.4, 129.8, 131.0, 136.5, 139.8. Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.64; H, 8.60.

***N*-Phenylmethyl-2-methyl-1-phenyl-3-buten-1-amine (22a, mixture of stereoisomers, *anti*/*syn* = 11/89):** IR (neat) 3333, 3063, 3026, 2970, 2799, 1638, 1603, 1495, 1454, 1362, 1198, 1115, 1072, 1028, 1001, 916, 845, 700 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.66 (d, J = 6.6 Hz, 0.33H), 0.89 (d, J = 6.6 Hz, 2.67H), 1.63 (bs, 1H), 2.23−2.35 (m, 0.11H), 2.36−2.49 (m, 0.89H), 3.11 (d, J = 8.7 Hz, 0.11H), 3.32 (d, J = 13.5 Hz, 0.11H), 3.40 (d, J = 13.5 Hz, 0.89H), 3.53 (d, J = 5.7 Hz, 0.89H), 3.53 (d, J = 13.5 Hz, 0.11H), 3.60 (d, J = 13.5 Hz, 0.89H), 4.89 (dd, J = 2.1, 10.2 Hz, 0.89H), 4.90 (dd, J = 2.1, 17.4 Hz, 0.89H), 5.00 (dd, J = 2.1, 10.2 Hz, 0.11H), 5.06 (dd, J = 2.1, 17.4 Hz, 0.11H), 5.61 (ddd, J = 7.2, 10.2, 17.4 Hz, 0.11H), 5.63 (ddd, J = 7.2, 10.2, 17.4 Hz, 0.89H), 7.10−7.27 (m, 10H); ^{13}C NMR ($CDCl_3$) for major isomer δ 15.41, 43.78, 51.46, 66.14, 114.72, 126.63, 126.71, 127.83, 127.98, 128.06, 128.14, 140.59, 140.93, 141.69; for minor isomer δ 17.9, 45.7, 51.3, 66.7, 115.9, 126.8, 127.0, 128.0, 128.0, 128.1, 128.3, 140.9, 142.1, 142.3. Anal. Calcd for $C_{18}H_{21}N$: C, 86.01; H, 8.42. Found: C, 85.97; H, 8.39.

***N*-Phenylmethyl-2,4-dimethyl-5-hexen-3-amine (22b, mixture of stereoisomers, *anti*/*syn* = 17/83):** IR (neat) 3352, 3065, 3028, 2961, 2872, 1639, 1605, 1495, 1454, 1369, 1292, 1101, 1028, 999, 910, 741, 698 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.94 (d, J = 10.8 Hz, 2.49H), 0.96 (d, J = 10.8 Hz, 2.49H), 0.96 (d, J = 8.4 Hz, 0.51H), 0.98 (d, J = 8.4 Hz, 0.51H), 1.07 (d, J = 6.9 Hz, 0.51H), 1.07 (d, J = 6.9 Hz, 2.49H), 1.38 (bs, 1H), 1.75−1.89 (m, 1H), 2.16 (dd, J = 5.7, 5.7 Hz, 0.17H), 2.22 (dd, J = 5.7, 5.7 Hz, 0.83H), 2.31−2.48 (m, 1H), 3.82 (d, J = 6.3 Hz, 2H), 4.99 (dd, J = 1.8, 10.2 Hz, 1H), 5.03 (dd, J = 1.8, 17.7 Hz, 1H), 5.86 (ddd, J = 7.8, 10.2, 17.7 Hz, 0.83H), 5.87 (ddd, J = 7.8, 10.2, 17.7 Hz, 0.17H), 7.20−7.39 (m, 5H); ^{13}C

(16) Matsumoto, K.; Oshima, K.; Utimoto, K. *J. Org. Chem.* **1994**, *59*, 7152.

(17) Tan, K. T.; Chng, S. S.; Cheng, H. S.; Loh, T. P. *J. Am. Chem. Soc.* **2003**, *125*, 2958.

NMR ($CDCl_3$) for major isomer δ 15.7, 18.0, 21.5, 30.8, 41.1, 55.4, 67.3, 113.2, 126.7, 128.1, 128.1, 141.2, 143.4; for minor isomer δ 15.7, 18.2, 20.8, 30.9, 41.2, 55.4, 67.4, 114.3, 126.,7, 128.1, 128.1, 141.2, 142.1. Anal. Calcd for $C_{15}H_{23}N$: C, 82.89; H, 10.67. Found: C, 82.78; H, 10.38.

***N*-Phenylmethyl-1-cyclohexyl-2-methyl-3-buten-1-amine (22c: mixture of stereoisomers, *anti*/*syn* = 18/82):** IR (neat) 3350, 3065, 3028, 2924, 2853, 1638, 1602, 1495, 1450, 1418, 1072, 1028, 999, 968, 908, 698 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.96 (d, J = 6.9 Hz, 2.46H), 0.97 (d, J = 6.9 Hz, 0.54H), 1.08−1.25 (m, 5H), 1.31−1.44 (m, 1H), 1.52 (bs, 1H), 1.53−1.79 (m, 5H), 2.07 (dd, J = 5.4, 5.4 Hz, 0.18H), 2.14 (dd, J = 5.4, 5.4 Hz, 0.82H), 2.27−2.43 (m, 1H), 3.70 (d, J = 2.7 Hz, 2H), 4.91 (dd, J = 1.8, 10.2 Hz, 1H), 4.94 (dd, J = 1.8, 17.4 Hz, 1H), 5.78 (ddd, J = 7.2, 10.2, 17.4 Hz, 0.82H), 5.79 (ddd, J = 7.2, 10.2, 17.4 Hz, 0.18H), 7.13−7.30 (m, 5H); ^{13}C NMR ($CDCl_3$) for major isomer δ 15.2, 26.6, 26.7, 26.8, 28.8, 31.4, 40.2, 41.3, 55.5, 66.8, 113.2, 126.7, 128.1, 128.1, 141.2, 143.4; for minor isomer δ 18.2, 26.7, 26.8, 26.9, 28.8, 31.1, 40.4, 41.7, 55.5, 66.9, 114.3, 126.7, 128.1, 128.1, 141.2, 142.0. Anal. Calcd for $C_{18}H_{27}N$: C, 83.99; H, 10.57. Found: C, 84.08; H, 10.72.

Acknowledgment. This work was supported by a Grant-in-Aid for Scientific Research and COE Research from the Ministry of Education, Culture, Sports, Science, and Technology, Japan. K.F. acknowledges JSPS for financial support.

JO049863R