Development of Novel Carbon-Carbon Bond Formation Reactions using Organozirconium Complexes

有機ジルコニウム錯体を用いた新規な炭素－炭素結合生成反応の開発

Hideyuki OSUMI

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by
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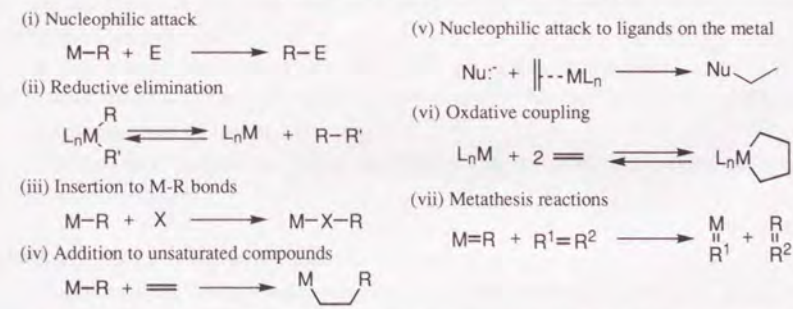
Chapter 1. General Introduction

Basic Pattern of C-C Bond Formation in Organometallic Chemistry

Recent development of organometallic chemistry is remarkable and extensive investigation was performed for its application to organic synthesis. Usage of organometallic compounds for organic synthesis as reagents, intermediates or catalysts has developed for the last several decades. Among them, the formation of a new carbon-carbon bond is one of the most attractive subject. Indeed, many useful reactions were reported so far and well established involving late transition metals such as palladium, nickel, cobalt and so on. On the other hand, these region on early transition metals such as zirconium, hafnium is rather young chemistry compared with that of late transition metal, and now it is explosively developing. To design a catalytic cycle for C-C bond formation using early transition metals is attractive since new aspects of transition metal catalyzed reaction are expected to be found based on the peculiar character of early transition metals. The author chose zirconium of a group 4 metal because many attractive but often stoichiometric synthetic reactions using zirconium compounds have appeared for these decades. Improvement of these chemistry to construct catalytic reaction is valuable and the reactions would be versatile.

There can be found several basic patterns for C-C bond formation reactions as follows; (i) nucleophilic attack of M-R to a positive-charged carbon like as C=O, C=N etc.; (ii) reductive elimination from $MR^1R^2L_n$ to give R^1-R^2; (iii) insertion of compounds with lone pair such as CO, RNC to M-R bond; (iv) addition of M-R to unsaturated compounds; (v) nucleophilic (or electrophilic) attack to ligand on a metal; (vi) oxidative coupling of unsaturated compounds on a metal; (vii) metathesis reactions that involve M=C (Scheme 1.1).

Scheme 1.1 Basic Patterns that Involve C-C Bond Formations in Organometallic Chemistry

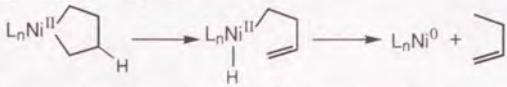


Particularly two-electron oxidation-reduction process ((ii) and (vi) in scheme 1.1 are the cases) is one of the most important process and often found in late transition metal catalyzed C-C bond formation. Ni or Pd catalyzed coupling of R-X and R'MgX' reported by Kumada et al. is one good example[1] (eq 1.1). Oxidative addition of R-X to Ni^0 that gives $Ni^{II}(X)R$, and reductive elimination from $Ni^{II}RR'$ to afford R-R' are main processes in the catalytic cycle. It should be

noted, however, that not only oxidation-reduction process but also transmetalation between Ni or Pd and Mg which transform $Ni^{II}(X)R$ to $Ni^{II}RR'$ plays indispensable role to construct the catalytic cycle.

$$\text{R-X} + \text{R'MgX'} \xrightarrow{\text{cat. } Ni^0 \text{ or } Pd^0} \text{R-R'} \qquad (1.1)$$

Oxidative coupling (pattern (iv)) gives an oxidized metalacyclic compounds. Also in this case the high valent metalacycle should be converted somehow to reduced species to participate in a catalytic C-C bond formation. For example in Ni^{II}, β-elimination and subsequent reductive elimination regenerate Ni^0 (eq 1.2).



(1.2)

In concern with early transition metals, especially in metallocene of group 4 elements ($Cp_2MR^1R^2$), reductive elimination of MR^1R^2 is rarely found. In zirconocene complexes, only few examples have been reported[2] while evolution of RH from $Cp_2Zr(H)R$ is rather easier.[3] This must be one reason why less examples of catalytic C-C bond formation using group 4 elements were reported compared to those using late transition metals. On the other hand oxdative coupling (pattern (iv)) is rather common reaction in early transition metals. In this two electron oxidation step, reduced species should be involved. Since group 4 metals usually show M^{2+} or M^{4+}, it is necessary to generate reduced species Cp_2M^{2+}. Ti tends to show also M^{3+}, the author chose zirconium because of this tendency of Ti. Also in early transition metal chemistry, in order to circulate a catalytic cycle, reduction process of metalacycle is required. In addition, transmetalation and/or β-elimination would play a important role in the reaction.

Again, following two points must be emphasized to design a catalytic cycle of C-C bond formation with group 4 metals.

(i) M^{2+} species would be a reduced species and M^{4+} will stay as a oxidized one.

(ii) Transmetalation and/or β-elimination processes would take part in a catalytic cycle to help regenerate a reduced species.

To begin the introduction the author would like to look back briefly the historical background of zirconium chemistry.

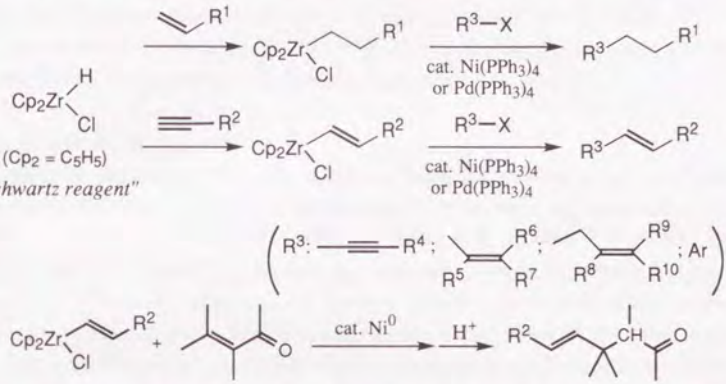
Historical Background of Zirconium Chemistry[4]

Reactions using Group 4 metal compounds as Lewis acid reagents are rather common, in which the metal compound activates an electrophile to react with a nucleophile.[5] Although nucleophilic C-C bond formation with alkylzirconium are known in $RZr(OR')_3$,[6] zirconocene compounds which are commonly used as zirconium reagents have rather low nucleophilicity. In late transition metal complexes, a reduction-oxidation cycle, for example, a combination of oxdative addition and reductive elimination, plays an important role in the carbon-carbon bond

formation reactions. It was very rare, however, in zirconium chemistry until some catalytic reactions recently appeared.

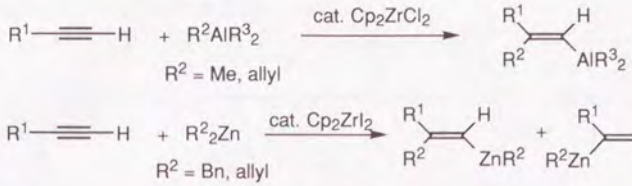
The first systematic use of zirconium in organic synthesis probably came out about two decades ago when Schwartz and Hart[7] began developing hydrozirconation, which had been discovered earlier by Wailes and Weigold.[8] This reaction made alkyl- and alkenylzirconium

Scheme 1.2 Hydrozirconation And C-C Bond Formation of Its Products



derivatives readily available. These organozirconium derivatives serve as useful intermediates for the preparation of organic halides, alcohols, and other hetero-substituted derivatives. In concern with the new C-C bond formation, in addition to carbonylation and acylation with acyl halides, Pd or Ni catalyzed cross coupling[9] and Ni catalyzed conjugate addition[10] significantly increased the synthetic utility of hydrozirconation products (Scheme 1.2). Since the C-Zr bond is relatively nonnuclephilic, the Ni- or Pd-catalyzed cross- coupling reaction has provided a useful means of effectively enhancing the nucleophilicity of the C-Zr bond.

Shortly thereafter, Negishi et al. discovered zirconium catalyzed carboalumination (eq 1.3)[11] and carbozincation (eq 1.4)[12] of alkynes. The reactions of alkynes with Me_3Al-Cp_2ZrCl_2 gives (*E*)-2-methyl-1-alkenylalanes. The reaction proceeds via essentially >98% syn addition. The regioselectivity of methylalumination is typically ca. 95% in good to excellent yield. This reaction is tolerant to various functional groups, such as hydroxyl, silyloxy and SPh, halogens. The carboaluminated products are versatile and can be replaced with variety of organic and organometallic compounds. These reactions are the pioneering work of zirconocene catalyzed C-C bond formations .



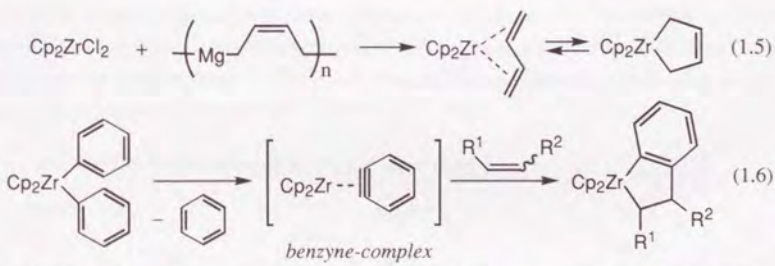
(1.3)

(1.4)

The olefin polymerization also involves C-C bond formation. Since Kaminsky discovered homogeneous olefin polymerization catalyst,[13] this area also have explosively developed mainly toward mechanistic investigation and its industrial application.

Preparation of Zr(II) Species

So far above described was organozirconium chemistry that are implicated to Zr(IV) species represented by Cp_2ZrXY. These species contains d^0, 16-electron and have no lone pair of electrons. So they do not readily form stable complexes with π-donors. "$Cp_2Zr(II)$", on the other hand, with d^2, 14-electron will show high activity, although 'real Cp_2Zr' has not been observed yet. Yasuda and Nakamura are pioneers of chemistry of Zr(II) species as well as Erker.[14] They generated zirconocene(II) species by treating Cp_2ZrCl_2 with metal such as Na and Mg, or with endiylmagnesium to give the zirconocene-butadiene complexes and its derivatives (eq 1.5). Erker reported formation of Cp_2ZrPh_2 and its reaction which give zirconocene-benzyne complex which is also show a character of Zr(II) (eq 1.6)[15].

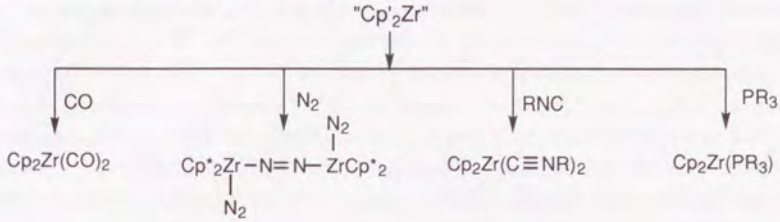


(1.5)

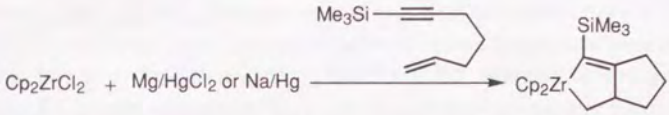
(1.6)

"$Cp_2Zr(II)$" used to be generated using Na or Mg which was common reduction procedure. Some Zr(II) complexes were prepared by this method as shown in scheme 1.3.

Scheme 1.3 Preparation of Zr(II) Complexes



The first reaction of "Cp_2Zr" with unconjugated enynes that provides bicyclized metalacycles were also reported using $Mg/HgCl_2$ as an reducing agent (eq 1.7).[16]

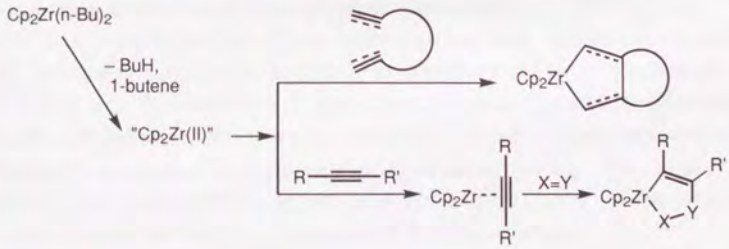


(1.7)

Initial exploration on $Cp_2Zr(II)$ was focused mainly on zirconocene-alkyne complexes. Zirconocene-benzyne complex is also one of them. Preparation and reactions of zirconocene-alkyne complexes have been investigated by several groups.[17]

A convenient method for generating $Cp_2Zr(II)$ was developed by Negishi et al.[17a] They treated Cp_2ZrCl_2 with 2 equiv of *n*-butyllithium. The reaction gives first $Cp_2Zr(n\text{-}Bu)_2$ (Negishi reagent), then finally "Cp_2Zr" equivalent. Treatment of $Cp_2Zr(n\text{-}Bu)_2$ with enynes, diynes or dienes[18] gave bicyclic metalacycles (Scheme 1.4). Thus, many attractive reactions which involve zirconocene-alkyne complexes[17c,d,19,20] and intramolecular cyclization reactions using zirconium have been intensively studied.[16,17a,f,18,19d,21,22,23,24,25,26]

Scheme 1.4 Negishi reagent as "Cp_2Zr" equivalent



Preparation of Zirconocene(II)-Alkene Complexes

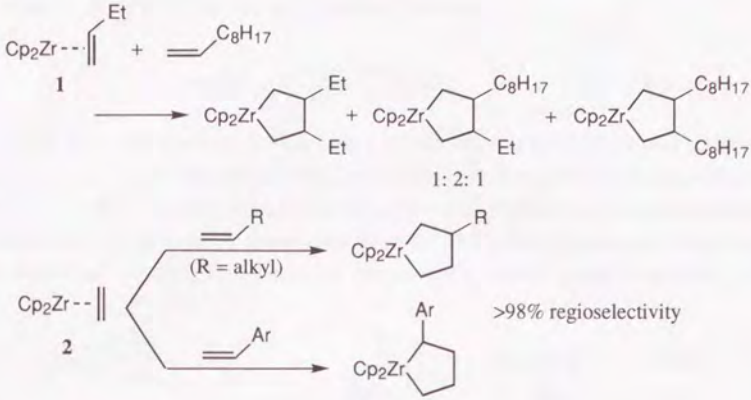
The preparation of alkene-zirconocene complexes and their reactivity was recently reported by Takahashi et al.[17a,c,f,27,28] They reported the first X-ray structure of zirconocene-stilbene complex.[27a] It had turned out later that Negishi reagent, $Cp_2Zr(n\text{-}Bu)_2$ proceeds smoothly β-hydrogen elimination and reductive elimination to gives finally, as a matter of fact, Cp_2Zr(1-butene) as a product. Although Cp_2Zr(1-butene) is not stable enough to be detected, in the presence of phosphine, Cp_2Zr(1-butene)(PMe_3) was obtained quantitatively. Since a weak ligand 1-butene plugged the orbital of "Cp_2Zr", 1-butene was easily substituted during the reaction with diynes or enynes. Thus $Cp_2Zr(n\text{-}Bu)_2$ can behave as Cp_2Zr(II) equivalent. Cp_2ZrEt_2, which can be prepared from Cp_2ZrCl_2 with EtMgBr for example, also give zirconocene-ethylene complex. Preparation of zirconocene-alkene complexes are summarized as follows; (i) addition of alkenes to Cp_2ZrBu_2 (Negishi reagent), (ii) addition of alkenes to $Cp_2Zr(PMe_3)_2$,[28a] (iii) a β-hydrogen abstraction and an elimination of alkanes from zirconocenedialkyls,[17d,28b,29] (iv) a reaction of Cp_2ZrMe_2 with alkylmagnesium halides,[27d] (v) replacement of alkenes in zirconocene-alkene complexes Cp_2Zr(alkene)(PR_3),[27e,28b] (vi) β-β' carbon-carbon bond cleavage of a zirconacyclopentane compound,[27b] or (vii) a reaction of zirconocene alkylalkoxides with alkylmagnesium halides.[30]

Takahashi et al. have intensively investigated the reactivity of zirconocene-alkene complexes particularly that of zirconocene-ethylene complexes as described below.[20,27c,30,31]

Regio- and "Pair"-selective Coupling of $Cp_2Zr(CH_2{=}CH_2)$ with Alkenes. The reaction of Cp_2Zr(1-butene) generated *in situ* from $Cp_2Zr(n\text{-}Bu)_2$ with an alkene gives a mixture of three possible zirconacyclopentanes in an essentially statistical ratio.[32] It is therefore not a "pair"-selective reaction (Scheme 1.5). In sharp contrast, the reaction of **2** generated *in situ* from Cp_2ZrEt_2 with 1-decene gave, after hydrolysis, only the cross coupling product, 3-methylundecane, as a >98% isomerically pure species. The homo coupling product of 1-decene was not detected by GLC. Thus, the reaction of **2** with 1-decene is highly 'pair'-selective. Treatment of the reaction mixture with D_2SO_4 and I_2 produced 3-(deuteriomethyl)-1-deuterioundecane and 1,4-diiodo-2-(*n*-octyl)butane, respectively.

The "pair"-selective reaction of **2** was observed not only with 1-decene but also with other alkenes including styrene, β-methylstyrene. It is noteworthy that the alkyl substituent of an alkene ends up in the β-position of the zirconacyclopentane products, and the phenyl group in the α-position. The regioselectivity in each case was >98%. This type of highly regioselective C-C bond formation are observed in Cp_2Zr-promoted alkene-alkene coupling. They suggested that steric factors favor the β-position in the cases of alkyl-substituted alkenes, whereas benzylic (π- and/or agostic) stabilization must favor placement of Ph in the α-position.

Scheme 1.5

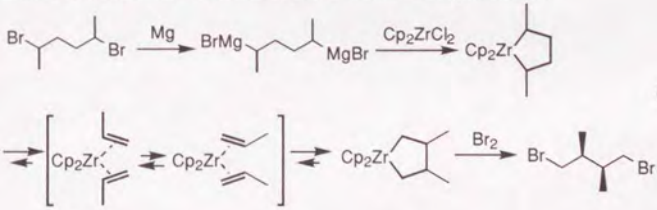


Zirconium Mediated Skeletal Rearrangement

Takahashi et al. elegantly applied the high regioselective formation of zirconacyclopentanes for skeletal rearrangement of hydrocarbons, 2,5-dibromohexane to *rac*-1,4-dibromo-2,3-dimethylbutane (eq 1.8).[31a]

(1.8)

They transformed the bromide to a Grignard reagent and treated it with Cp_2ZrCl_2. Formed zirconacyclopentane which has two methyl groups at its α-position show β-β'-C-C bond activation to isomerize into a thermodynamically more stable form. Brominolysis of the products afford the final compound with excellent diastereoselectivity (eq 1.9). These method for transformation of a molecular skeleton is quite unusual and sophisticated.

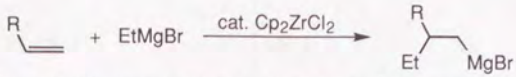


(1.9)

Zirconium Catalyzed C-C Bond Formation Reaction

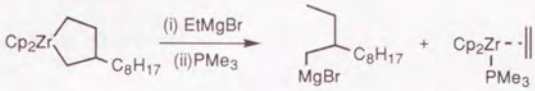
Recently Zr catalyzed C-C bond formation reactions via Zr-alkene complexes have been reported.[25a,33] Total reaction was zirconium catalyzed ethylmagnesation of terminal alkenes as

shown in eq 1.10. Takahashi et al., however, revealed that this reaction can be understood as zirconium catalyzed cross coupling of ethylene and alkenes.



(1.10)

They found that treatment of 3-(*n*-octyl)-1,1-bis(η^5-cyclopentadienyl)zirconacyclopentane (**3**) with 1 equiv each of EtMgBr and PMe_3 gave a ring-opened monomagnesio derivative **4** and **1a** (eq 1.11). Their results indicate that one of the two carbon atoms attached to zirconium in **3** is transferred from zirconium to magnesium, while the other carbon abstracts a hydrogen which must be derived from EtMgBr, leading to the formation of a mono-Grignard compound **4**.



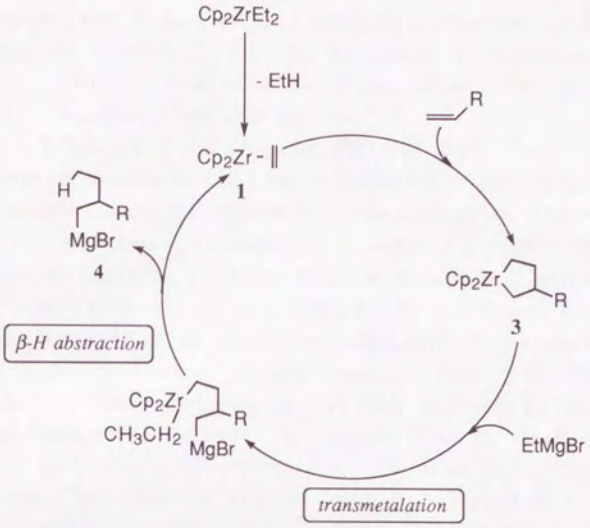
(1.11)

3 **4** (82% yield) **1a** (>63% yield)

From these results, zirconocene-ethylene complex **1** reacts with 1-decene to give **3**, and **3** reacts with EtMgBr to give product **4** and regenerate **1**. So they described a proposed catalytic cycle (Figure 1.1). That mechanism involves reduction-oxidation cycle between Zr(II) and Zr(IV). This transformation of oxidation state of catalyst metal is novel in early transition metals, while quite conventional pattern in late transition metal catalysts.

Now catalytic C-C bond formation with zirconium is very attractive area, and several other attractive reactions have been also reported.[34]

Figure 1.1 Proposed Mechanism for Catalytic Alkene-Coupling



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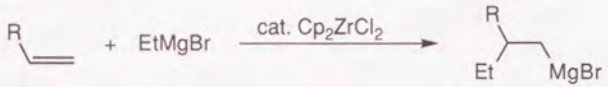
Chapter 2. Mechanistic Consideration on Zirconium Catalyzed Alkene-Alkene Coupling Reaction: Basic Patterns

Abstract: Mechanism of zirconium-catalyzed highly selective carbon-carbon bond formation reaction of EtMgBr with olefins has been investigated. Zirconocene dichloride reacted with 2 equiv of EtMgBr to give diethylzirconocene which was converted into an active zirconocene-ethylene complex $Cp_2Zr(CH_2{=}CH_2)$. This specie was stabilized as an ate complex, $[Cp_2ZrEt(CH_2{=}CH_2)]MgBr$, in the presence of an excess of EtMgBr. In transmetalation of dialkylzirconocene and ethylmagnesium a sterically hindered alkyl group tend to transfer to magnesium leaving zirconocene species. Kinetic study on selective β-hydrogen abstraction also support the proposed catalytic cycle. The use of higher alkylmagnesium derivatives such as *n*-OctMgCl instead of EtMgBr in the reaction with 1-octene in the presence of catalytic amount of Cp_2ZrCl_2 (0.03 equiv) afforded 9-methyl-6-pentadecene (92% based on *n*-OctMgCl). Cyclic alkenes conjugated with an aromatic ring such as indene and 1,2-dihydronaphthalene reacted with EtMgBr in the presence of a catalytic amount of Cp_2ZrCl_2 to give, after hydrolysis, the desired ethylated products in good yields with excellent regioselectivity.

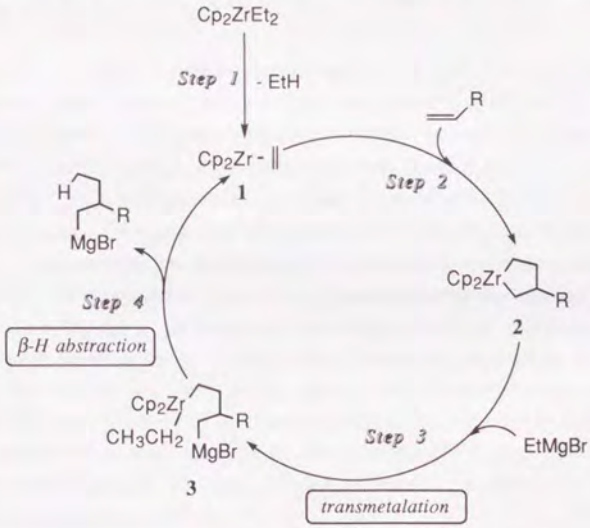
Introduction

Metal-catalyzed highly selective C-C bond formation reactions are highly attractive from the viewpoint of organic synthesis. As introduced in the previous chapter, Takahashi et al., colleagues of the author, have recently reported the preparation of zirconocene-alkene complexes and their reactivity[1] and that the combination of the reactions involving the zirconium-ethylene complex constructs totally the catalytic cycle of ethylmagnesation of terminal alkenes (Figure 2.1).[2,3] In fact, the overall catalytic process (eq 2.1) had been previously reported by Dzhemilev *et al.*,[4] in which reports they did not mention the mechanism of the reaction. This catalytic reaction is supposed to consist of following four steps; (i) the formation of zirconocene-ethylene complexes by the reaction of Cp_2ZrCl_2 with EtMgBr (step 1), (ii) "pair"-selective and regio-selective coupling of ethylene and alkenes (step 2), (iii) highly selective transmetalation reactions (step 3), and (iv) selective β-hydrogen abstraction reactions (step 4).



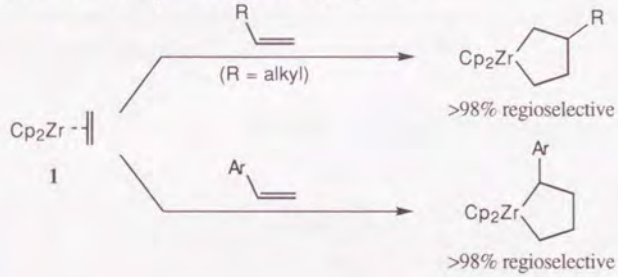
(2.1)

Figure 2.1 Proposed Mechanism for Catalytic Alkene-Alkene Coupling



Each step was well investigated by Takahashi and co-workers.[2] In concern with step 1, the formation of zirconocene-alkene complex from corresponding dialkylzirconocene was reported

and the complexes were isolated as phosphine adducts which are stabilized form.[5,6] The ready availability of zirconocene-alkene complexes led to investigation of their reactions with various compounds. The formation of **1**, however, had not been detected because of its unstability. 'Pair'-selective coupling of ethylene and alkenes (step 2) are the area that was investigated most deeply (eq 2.2).[1] The reaction of **1** generated *in situ* from Cp_2ZrEt_2 with 1-decene gave, after hydrolysis, only the cross coupling product, 3-methylundecane, in good yield as a >98% isomerically pure species. The homo coupling product of 1-decene was not detected. Thus, the reaction of **1** with 1-decene is highly 'pair'-selective. Using aromatic substituted alkenes such as styrene also showed high 'pair'-selectivity but with opposite regioselectivity. Aromatic substituents came to α-position in zirconacyclopentanes.



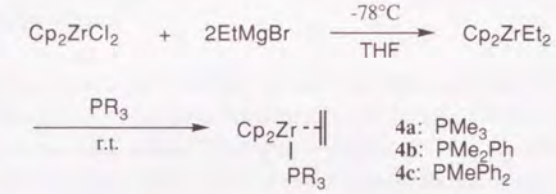
(2.2)

They also investigated transmetalation reactions of these zirconacyclopentanes with ethylmagnesium bromide and proposed some experimental evidences for the selective transmetalation (step 3). The β-hydrogen abstraction reaction (step 4) of dialkylzirconocenes which results in zirconocene-alkene complexes was also reported partly.[5f] Although various different mechanisms for carbometalation of alkenes and alkynes have been proposed[7] and clarified in some cases, the four-step mechanism they proposed appears to be unprecedented. It also points to a fundamentally new catalytic pattern involving early transition metal complexes. In fact mechanistic investigation of this catalytic reaction turned out later to give important information on a zirconium catalyzed novel allylation reaction that will be described in next chapter. I have therefore further investigated the elementary steps which are thought to be involved in this catalytic reaction. In this chapter I describe details of (i) the formation of zirconocene-ethylene complexes by the reaction of Cp_2ZrCl_2 with EtMgBr (step 1), (ii) highly selective transmetalation reactions (step 3), (iii) kinetic study on the selective β-hydrogen abstraction reactions (step 4). I further describe the results of my study of a few related Zr-catalyzed carbomagnesation reactions.

Results and Discussion

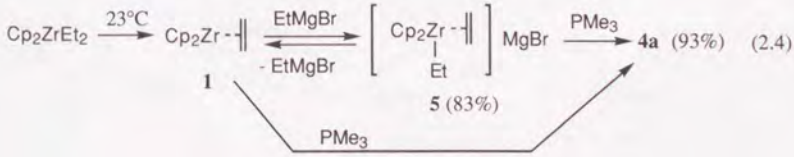
Formation of Zirconocene-Ethylene Complexes And Kinetic Study on Its Stability.

Takahashi et al. have recently reported several methods for the preparation of alkene-zirconocene complexes[5,6] and spectroscopically and chemically characterized them. One such complex, i.e., $Cp_2Zr(PhCH{=}CHPh)(PMe_3)$, yielded the first X-ray structure of an alkene-zirconocene complex.[5c] When Cp_2ZrCl_2 was treated with EtMgBr at -78°C, Cp_2ZrEt_2 was quantitatively formed *in situ*. After addition of PR_3 such as PMe_3, PMe_2Ph and $PMePh_2$, Cp_2ZrEt_2 was gradually converted at room temperature into the zirconocene ethylene complexes $[Cp_2Zr(CH_2{=}CH_2)(PR_3)]$ **4a-c** in >90% yields. Alt et al.[6a] and Binger et al.[6b] independently reported the formation of the same complex **4a** by the reaction of $Cp_2Zr(PMe_3)_2$ with an ethylene gas (50 bar) and by the reaction of Cp_2ZrCl_2 with EtMgI, respectively. The structure of this complex was determined by X-ray analysis by Alt et al.[6a]



(2.3)

The complex **4** was very stable. Addition of a 1-alkene such as 1-octene to **4** did not give the expected zirconacyclopentane derivatives in which ethylene and the 1-alkene are coupled. To generate real active zirconocene-ethylene species, the reaction of Cp_2ZrCl_2 with 2 equiv of EtMgBr in the absence of phosphines was investigated. The ^1H NMR spectrum of the reaction mixture indicated the formation of $Cp_2Zr(CH_2{=}CH_2)$ (**1**). Thus the signal assignable to ethylene protons appeared as a broad singlet at 0.7 ppm. This broad singlet disappeared when PMe_3 was added to **1** and the characteristic ethylene protons of **4a** emerged. The ^{13}C NMR signal for the ethylene carbons of **1** at 33.30 ppm also disappeared, and two nonequivalent ethylene carbon signals of **4a** at 14.74 and 18.51 ppm emerged on addition of PMe_3.



(2.4)

Addition of one equiv of EtMgBr to **1** gave a new species, tentatively identified as a zirconate complex $[Cp_2ZrEt(CH_2{=}CH_2)]MgBr$ (**5**) in 83% NMR yield. Addition of one

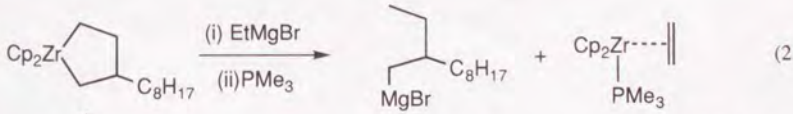
additional equiv of EtMgBr did not change the NMR spectrum of **5**. The same complex was also generated by the reaction of Cp_2ZrCl_2 with 3 equiv of EtMgBr. The ^1H NMR spectrum of **5** showed a distinctly broad singlet at 5.3 ppm assignable to the Cp protons. The two methylene groups of the ethylene moiety of **5** were nonequivalent and then ^1H NMR signals appeared at 0.51 and -0.50 ppm. When one equiv of PMe_3 was added to **5**, **4a** was formed in 93% yield along with free EtMgBr regenerated to the extent of 66%.

Decomposition of **1** and **5** displayed first order kinetics, and the rate constants were 2.2 x 10^{-4} and 4.2 x 10^{-5} sec^{-1} at 23 °C, respectively. Addition of one additional equivalent of EtMgBr to **5** showed down its decomposition (k_1 = 1.6 x 10^{-5} sec^{-1}). Clearly, **1** is stabilized by the formation of **5** which, in turn, can be further stabilized by an additional equivalent of free EtMgBr. Under the reaction condition of the zirconium catalyzed C-C bond formation of alkenes, an excess EtMgBr always exist around zirconium species. In that sense, the zirconium-ethylene complex **1**, which is an active species in the reaction, was stabilized by EtMgBr in the actual reaction mixture.

Ring-Opening Transmetalation Reaction of Zirconacyclopentanes with EtMgBr

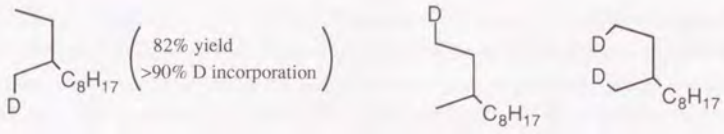
In the catalytic cycle drawn in Figure 2.1, 'step 3' shows a transmetalation reaction of the product moiety from Zr to Mg. The transmetalation possibly can take place at either (or both) of two Zr-carbon bonds. Takahashi et al. revealed that this reaction, as a matter of fact, selectively proceeds.

They have reported that treatment of 3-(*n*-octyl)-1,1-bis(η^5-cyclopentadienyl)-zirconacyclopentane (**6**) with 1 equiv each of EtMgBr and PMe_3 gave a ring-opened monomagnesio derivative **7** accompanying with **4a** (eq 2.5). When the products were quenched with D_2SO_4, 3-(deuteriomethyl)undecane (**8**) was obtained, and its regioisomer, i.e., 1-deuterio-3-methylundecane **9** and the dideuterated product **10** were not detected. These results strongly indicate that one of the two carbon atoms attached to zirconium in **6** is transferred from zirconium to magnesium, while the other carbon abstracts a hydrogen which must be derived from EtMgBr, leading to the formation of a mono-Grignard compound **7**, rather than a di-Grignard species, along with **1** (or **5** in the presence an excess of EtMgBr).



(2.5)

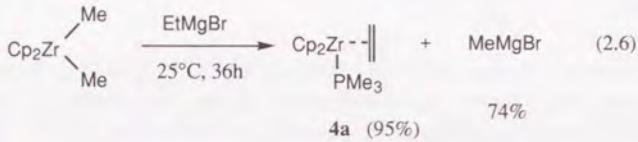
6 **7** (82% yield) **4a** (>63% yield)



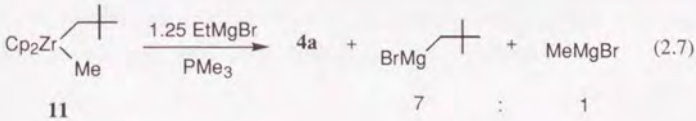
8 **9** **10**

The two carbons attached to zirconium in **6** are differentiated due to the *n*-octyl substituent. Namely, the carbon closer to the *n*-octyl substituent is selectively transferred from zirconium to magnesium. This selectivity is quite unexpected and noteworthy. I describe in this section the investigation that shed light on this unusual selectivity.

The transmetalation reaction accompanied by abstraction of a hydrogen from EtMgBr to form an ethylene-zirconocene complex was also observed with acyclic dialkylzirconocene derivatives, such as Cp_2ZrMe_2.[5g] Treatment of Cp_2ZrMe_2 with 1 equiv of EtMgBr in THF gave **4a** in the presence of PMe_3 along with MeMgBr (eq 2.6).



To probe the steric effects on regioselectivity, **11** was treated with 1.25 equiv of EtMgBr. The reaction provided neopentylmagnesium bromide and methylmagnesium bromide in a 7:1 ratio (eq 2.7). The formation of **4a** was also observed in the presence of 1.1 equiv of PMe_3. Although the product ratio is lower than we expected, the results support our notion that the sterically more hindered of the two alkyl groups on Zr, i.e., neopentyl in this case, is preferentially transferred to Mg. This result is consistent with the selectivity in the transmetalation of **6**.

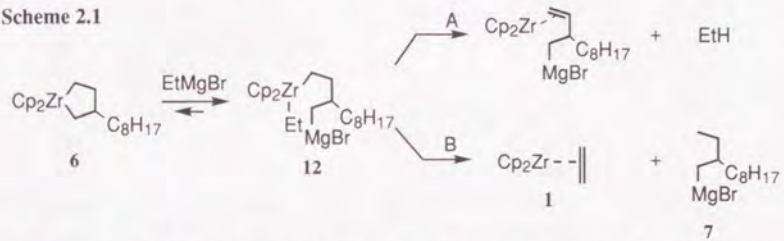


Highly Regioselective β-Hydrogen Abstraction Reaction of Dialkylzirconocenes

Conversion of 3-(*n*-octyl)-1,1-bis(η^5-cyclopentadienyl)zirconacyclopentane (**6**) to 2-ethyldecylmagnesium bromide (**7**) and $Cp_2Zr(CH_2{=}CH_2)$ (**1**) via presumed transmetalation followed by β-hydrogen abstraction requires not only a highly regioselective transmetalation

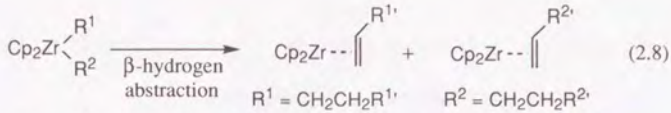
process discussed above but also a highly regioselective β-hydrogen abstraction reaction of a putative intermediate **12** since the reaction of **6** with EtMgBr via transmetalation and β-hydrogen abstraction can, in principle, occur by two possible competing processes, A and B, shown in Scheme 2.1. The question is that which alkyl group get β-hydrogen from the other to eliminate as an alkanes. For late transition metal dialkyls, Yamamoto et al. have reported similar thermal decomposition reactions of unsymmetrical dialkyl platinum complexes.[8] Our results, however, revealed particular character of β-elimination in zirconocene dialkyls and differ from that reported in square planar four-coordinate dialkyl metal complexes ($PtR^1R^2L_2$) as discussed below.

Scheme 2.1



Recently we have prepared "mixed" dialkylzirconocenes Cp_2ZrRR' from chloro(alkyl)zirconocenes and one equiv of alkyllithium, and studied β-hydrogen abstraction reaction by ^1H NMR spectroscopy in the presence or absence of 1 - 2 equiv of PMe_3. The experimental results summarized in Table 2.1 exhibit some unusual order of reactivity of alkyl groups as β-hydrogen donors. The β-hydrogen abstraction reaction of $Cp_2ZrEt(R)$, where R is *n*-Bu, *i*-Bu, *s*-Bu, and *t*-Bu, indicate the reactivity order: *s*-Bu > *t*-Bu > Et > *n*-Bu > *i*-Bu. These results indicate the ability of alkyl groups to provide its β-hydrogen is in this order: β-methyl > β-methylene > β-methine.

Though Yamamoto et al. reported similar tendency in thermal decomposition of *cis*-$PtR^1R^2L_2$, they reported the relative rate of β-elimination involving the R^1 to that involving the R^2 is proportional to the ratio of the number of β-hydrogen atoms in the R^1 group to that in R^2. That is, when R^1=Et and R^2=*n*-Pr, ratio of ethylene/propene was 3/2. Obviously our results show greater ratio than that of the number of β-hydrogen in each alkyl group. To simplify the rate of the elimination, we carried kinetic investigation with $Cp_2ZrMe(R)$



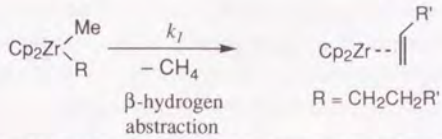
(2.8)

Table 2.1 Thermal Decomposition of Dialkylzirconocenes in the Presence of PMe_3

$Cp_2ZrR^1R^2$		Yield of $Cp_2Zr(alkene^i)(PMe_3)$,[a] /%		
R^1	R^2	$i = 1$	$i = 2$	total
Et	*n*-Bu	88	12	100
Et	*n*-Decyl	73	<3	73-76
Et	*i*-Bu	90	<2	90-92
Et	*n*-Hex(Et)$CHCH_2$	70	<2	70-72
Et	*s*-Bu	8	86	94
Et	*t*-Bu	12	53	65
Et	$PhCH_2CH_2$	28	52	80
n-Decyl	*i*-Bu	90	5	95
n-Decyl	*s*-Bu	<2	95	95-97
n-Decyl	*t*-Bu	9	82	91
n-Dodecyl	$PhCH_2CH_2$	10	87	97
n-Hex(Et)$CHCH_2$	*t*-Bu	<2	63	63-65

[a]Alkene^i (i = 1 and 2) are produced from R^i (i = 1 and 2), respectively. The products were stereoisomeric mixtures of the distal and proximal isomers except for $Cp_2Zr(CH_2{=}CH_2)(PMe_3)$. The combined amounts of the two isomers are shown.

Kinetic measurements of the first-order β-abstraction reaction of $Cp_2Zr(Me)R$ prepared by treatment of $Cp_2Zr(Me)Cl$[9] with one equivalent of RLi (Table 2.2) have further confirmed the reactivity. Clearly, the order of reactivity shown above does not correlate with the overall steric requirements of alkyl groups. On the other hand, all of the results with the exception of those cases where the $PhCH_2CH_2$ group is involved are in agreement with the generalization that the reactivity of alkyl ligands as β-hydrogen donors correlates with the degree of substitution at the β-carbon centers and that it decreased in the order: β-methyl > β-methylene > β-methine. The ratios of the rates in each case were much greater than that of the number of β-hydrogen atoms on the contrary to the report on platinum complexes.[8]



(2.9)

Table 2.2 The First-Order Rate Constants for the Reductive β-Elimination Reaction of Cp_2ZrMeR

R of Cp_2ZrMeR	rate constant (10^{-2} x k_1)min^{-1} a)			
	in the presence of PMe_3		in the absence of PMe_3	
s-Bu	3.65 (0 °C)		3.90 (0 °C)	
t-Bu	0.61 (0 °C)		0.52 (0 °C)	
Et	0.84 (0 °C)	5.23 (20 °C)	0.52 (0 °C)	5.05 (20 °C)
n-Bu		0.75 (20 °C)		0.83 (20 °C)
i-Bu		0.17 (20 °C)		0.19 (20 °C)

[a]The error range in each case was <10%.

A few additional comments are in order. First, there has been no sign of any interaction between Cp_2Zr-alkene-PMe_3 complexes with alkanes formed as byproducts. In this sense, the reaction must be essentially irreversible, and the observed results are kinetic rather than thermodynamic in nature. Second, the reaction rates are virtually unaffected by PMe_3 (Table 2.2). This conclusion has been further supported by the finding that addition of PMe_3 to Cp_2ZrMe_2 did not cause any detectable shift of the ^1H NMR Cp signal, indicating that even the sterically least demanding dialkylzirconocene, i.e., Cp_2ZrMe_2, does not detectably interact with PMe_3. Thus, the role of PMe_3 is merely to trap and stabilize the β-abstraction products in the form of Cp_2Zr-alkene-PMe_3. Third, the greater reactivity of $PhCH_2CH_2$ relative to that of Et is anomalous, but it may readily be accommodated by invoking benzylic stabilization. While predictive comparison within one category e.g., β-methyl containing Et, *s*-Bu, and *t*-Bu, remains to be difficult, this study permits some rationalization and prediction of the course of β-hydrogen abstraction of dialkylzirconocenes.

The results obtained here strongly support the notion that the putative intermediate **12** undergoes a highly regioselective β-hydrogen reaction to give **7** and **1** (Path B). Indeed, the β-hydrogen abstraction reaction of Cp_2ZrEt(decyl-*n*), where a β-CH_3 containing group, i.e., Et, competes with a β-CH_2 containing group, i.e., *n*-Decyl, the former nearly exclusively acts as the β-hydrogen donor. Thus, as in the transmetalation reaction, subtle structural differences in dialkylzirconocenes can lead to some strikingly regioselective β-hydrogen abstraction.

Conclusion: Mechanism of The Zirconium Catalyzed Ethylmagnesation of Alkenes

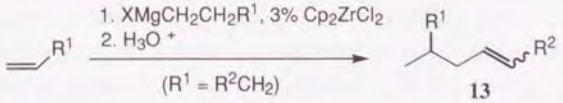
The present mechanistic studies on the zirconium-catalyzed C-C bond formation reaction (eq 2.1) support the proposed catalytic cycle shown in Figure 2.1. And these total studies have

thus not only unraveled the mechanism of the Zr-catalyzed ethylmagnesation of alkenes but also disclosed an unprecedented catalytic principle involving (i) decomposition of dialkylzirconocenes to give alkene-zirconocene complexes via β-hydrogen abstraction, (ii) their ring-expansion reaction with alkenes to give zirconacyclopentane derivatives, which can, in favorable cases, be highly "pair"- and regio-selective, (iii) ring-opening reaction of zirconacyclopentane derivatives with Grignard reagents via transmetalation which can be followed by β-hydrogen abstraction to regenerate alkene-zirconocene complexes for recycling of active zirconocene derivatives as catalysts. It is expected that many additional catalytic reactions involving all or some of these elementary steps can be developed, as indicated by the Zr-catalyzed hydrosilation[10] and hydrogenation[11] reactions as well as those results discussed in the following sections.

Use of Higher Alkylmagnesium Derivatives in the Zirconium-Catalyzed Alkylmagnesation of Alkenes

Dzhemilev has reported that the use of higher alkylmagnesium derivatives, such as n-Pr_2Mg and n-Bu_2Mg, in place of ethylmagnesium derivatives leads to the formation of mixtures of alkyl-incorporated alkanes and alkenes as well as dimers of the alkenes used in unspecified yields.[4b]

To gain more definitive information on these reactions we carried out the reaction of n-OctMgCl with 1-octene (5 equiv) in the presence of Cp_2ZrCl_2 (0.03 equiv) in THF at 60°C for 36h. It gave, after hydrolysis, 0.92 equiv (92% based on n-OctMgCl) of 9-methyl-6-pentadecene (**13d**) as a 4:1 mixture of the E and Z isomers (eq 2.10). Essentially the same results were obtained with preformed **14** (R^1 = n-Hex) used in place of Cp_2ZrCl_2. The results indicate that a zirconacyclopentane derivative can serve as a catalyst precursor or an intermediate. Similarly, the reaction of n-HexMgCl with 1-hexene gave a 4:1 E and Z stereoisomeric mixture of (**13e**) in 72% yield based on n-HexMgCl. The product yield depended on the amount of an alkene used. For example, the use of 2 equiv of 1-octene led to only a 21% yield of **13d** under otherwise the same conditions as above. The reaction of n-OctMgCl with 1-hexene (6.7 equiv) in the presence of 0.03 equiv of Cp_2ZrCl_2 provided predominantly **13e**, a hexene dimer, in 90% yield along with 10% of the two possible cross-coupling products and a trace of **13d**, indicating that the reaction must involve an alkene-alkene coupling.

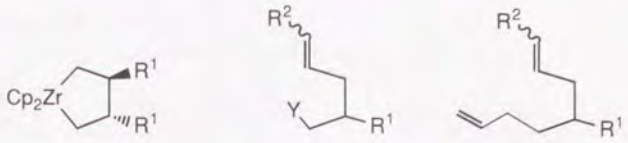


(2.10)

d: R^1 = n-Hex, R^2 = n-Pent, **e:** R^1 = n-Bu, R^2 = n-Pr, **f:** R^1 = Et, R^2 = Me

To further probe the mechanistic details of the reaction, the mixture derived from n-OctMgCl, 1-octene (5 equiv), and Cp_2ZrCl_2 (0.03 equiv) was quenched with DCl-D_2O in one run and with I_2 in THF in another. In each case, incorporation of D or I at the Me group on C-9

to give **15d** or **16d**, respectively, was observed to the extent of ca.50%, indicating that at least half of the product before quenching was **17d**. Similarly, deuterolysis and iodinolysis of the product derived from *n*-BuMgCl and 1-butene provided **15f** and **16f**, respectively, indicating the formation of **17f** as the organometallic product.



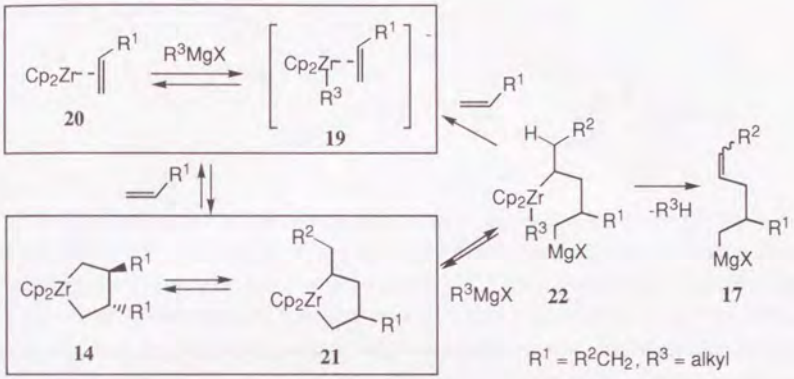
14 **15**: Y = D **18**
16: Y = I
17: Y = MgX

d: R^1 = n-Hex, R^2 = n-Pent, **e**: R^1 = n-Bu, R^2 = n-Pr, **f**: R^1 = Et, R^2 = Me

Treatment of a reaction mixture containing **17f** with allyl bromide provided a 40% yield (based on *n*-BuMgCl) of the expected product **18f** (E/Z = 80/20). The results indicate that the organometallic product is indeed a Grignard reagent **17f**. That the reaction most likely is catalyzed by a zirconocene-alkene complex has been indicated by the following. As presented earlier, treatment of Cp_2ZrCl_2 with 3 equiv of EtMgBr gives a zirconocene-ethylene complex which is the best represented by **5** formed via **1**. When **5** was treated with 1-octene (20 equiv) and MeMgBr (5 equiv) at 60°C for 24 h, 2.7 equiv (54% based on MeMgBr) of **13d** was formed. While some details are still unclear, the mechanism shown in Scheme 2.2 is consistent not only with the observed facts but also with the mechanism described above. Some salient features of the mechanism are as follows. First the reaction involves an alkene-alkene coupling from the view point of mechanism. Secondly, although alkylmagnesium derivatives serve as the limiting reagents, only a catalytic amount of an alkylmagnesium derivatives containing a β-hydrogen atom is required to initially generate zirconocene-alkene complexes, i.e., **19** and/or **20**. The Mg-incorporating and catalyst-regenerating roles can be played even by MeMgBr which lacks β-hydrogen atoms. One key assumption in Scheme 2.2 that remains to be further clarified is the intermediacy of **21**, which has not been observed in the stoichiometric reaction and is hence thought to be less stable than **14**. However, the highly labile nature of the C_β-C_β' bonds of zirconacyclopentanes with respect to ring contraction and carbon skeleton rearrangement has been well established. It is therefore reasonable to assume that **21** is kinetically accessible under the reaction conditions. Another key assumption that **21** is converted to **17** via **22** is closely analogous to that reported for the Zr-catalyzed ethylmagnesation of alkenes. Finally, **14** could, in principle, directly interact with a Grignard reagent to give a tail-to tail coupling product rather than **17**. Although the reason for the preferential formation of the head-to-tail coupling product **17** is still not very clear, our recent results indicate that reductive β-elimination of

dialkylzirconocene derivatives involving β-methylene groups is considerably faster than that involving β-methine groups. A tail-to-tail dimerization of propene to give 2,3-dimethyl-1-butene catalyzed by $Ti(\eta^4\text{-}C_4H_6)_2(dmpe)$ or $Zr(\eta^4\text{-}C_4H_6)_2(dmpe)$ is known.[12] However, the head-to-tail dimerization of monosubstituted alkenes appears to be novel.

Scheme 2.2

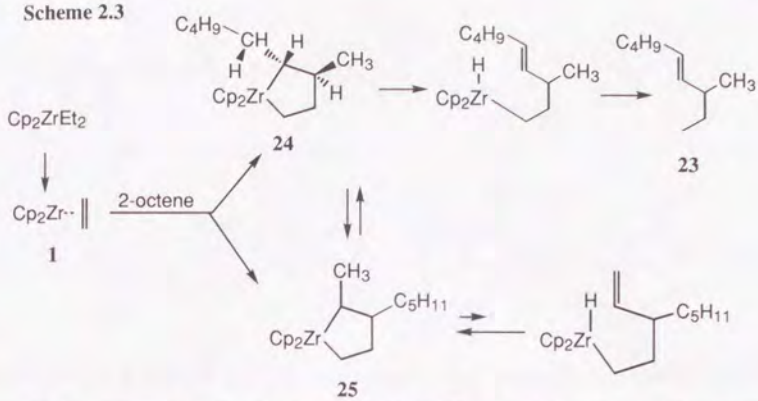


Zirconium-Catalyzed Ethylmagnesation of Internal Alkenes

Dzhemilev also reported the reaction of strained and highly reactive internal alkenes such as 2-norbornene with Et_2Mg and EtMgBr catalyzed by Cp_2ZrCl_2. The corresponding reaction of simple and less reactive internal alkenes, such as 2-octene and cyclopentene, remained essentially uninvestigated.

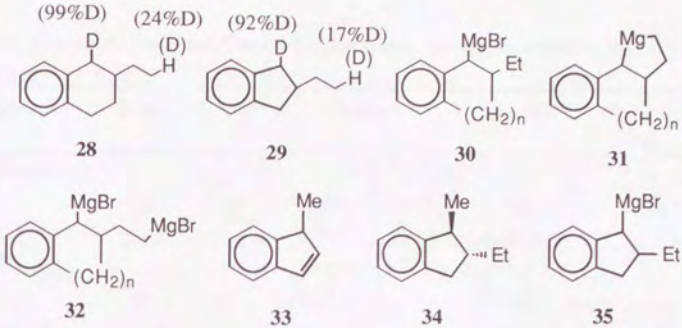
The reaction of 2-octene (E/Z = 73/27) with one equiv of $Cp_2Zr(CH_2{=}CH_2)$ (**2**) gave (*E*)-3-methyl-4-nonene (**23**) in 36% yield as the main product. However, 2-octene remained unreacted to the extent of 95% in the corresponding catalytic reaction using 10 mol % of Cp_2ZrCl_2 and 3 equiv of EtMgBr, the yield of **23** being ca.3 % (ca.30% based on Zr). Although some details are to be further clarified, the results can be accommodated by Scheme IV, in which some reasonable assumptions, such as (i) formation of **24** and **25** as a rapidly equilibrating mixture, and (ii) faster dehydrozirconation of **24** than that of **25** followed by reductive elimination to give **23** in a regio- and stereoselective manner, are made. In sharp contrast with the β-hydrogen abstraction reaction of dialkylzirconocenes discussed earlier, the β-dehydrozirconation reaction must be facilitated by sterically hindered alkyl groups.

Scheme 2.3



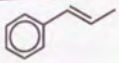
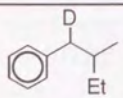
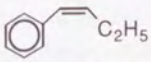
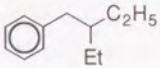
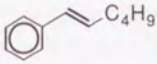
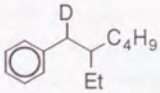
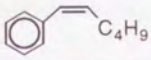
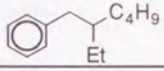
The Zr-catalyzed reaction of styrene with EtMgBr was much more favorable. Thus, for example, the reaction of β-methylstyrene with EtMgBr in the presence of 10 mol % of Cp_2ZrCl_2 gave, after protonolysis, 1-phenyl-2-methylbutane in 98% yield. Similarly, (*Z*)-β-ethylstyrene and (*E*)- and (*Z*)-β-butylstyrenes were converted to 1-phenyl-2-ethylbutane and 1-phenyl-2-ethylhexane, respectively, in good yields, although these reactions were relatively sluggish (Table 2.3). These favorable results are attributable to the fact that the reaction of (ethylene)zirconocene (*Z*) and styrene derivatives is highly "pair -" and regioselectively placing the Ph group in the α-position, which precludes the alkene-forming side reaction observed with non-arylated alkenes discussed above.

In a similar way cyclic alkenes conjugated with an aromatic ring such as 1,2-dihydronaphthalene and indene reacted with EtMgBr in the presence of a catalytic amount of Cp_2ZrCl_2 to give, after protonolysis, the desired ethylated products in good yields with excellent regioselectivity as shown in Table 2.4. Ethylation occurred exclusively in the β-position. Deuterolysis with DCl-D_2O gave **28** and **29** for **26** and **27**, respectively, indicating that the main organometallic products were **30**. Since deuterium was also incorporated at the terminal carbon atom of the ethyl group to the extents of 17-24% dimagnesio derivatives such as **31** and **32** must have also been formed as minor byproducts.



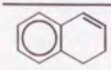
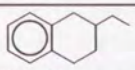
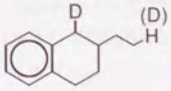
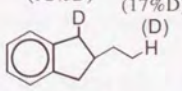
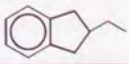
The reaction of 3-methylindene (**33**) was stereoselective producing only *trans*-1-methyl-2-ethylindane (**34**), after hydrolysis, and not even a trace of *cis*-isomer could be observed. On the other hand, treatment of a reaction mixture containing **35** with iodomethane (at room temperature for 12 h) gave **34** and its cis isomer in 55% combined yield (based on indene) as a 46/54 mixture.

Table 2.3 Zirconium Catalyzed Carbon-Carbon Bond Forming Reaction of Alkenylbenzenes with EtMgBr[a]

Substrate	Time/h	H^+/D^+	Product	Yield/%	Regiosel. /%
	24[b] (0°C)	D^+		98 (>96% D)	>98%
	70	H^+		47	>97
	58	D^+		58 (97% D)	>99
	48	H^+		38	>97

[a]Cp_2ZrCl_2: substrate : EtMgBr = 0.1 : 1 : 3; THF as a solvent; at room temperature. [b]Cp_2ZrCl_2: substrate : EtMgBr = 0.1 : 1 : 5 at 0°C.

Table 2.4 Carbon-Carbon Bond Forming Reaction of Cyclic Alkenylbenzenes with EtMgBr Catalyzed by Zirconocene Complex

Substrate	Temp /°C	Time /h	H^+/D^+	Product		Yield /%	Regiosel. /%
	0	12	H^+		**26**	84	>98
	r.t.	3	D^+	(99%D) (24%D) 	**28**	74	>98
	0	12	D^+	(92%D) (17%D) 	**29**	63	>99
	r.t.	1	H^+		**27**	67	>99

Cp_2ZrCl_2 : Substrate : EtMgBr = 0.1 : 1 : 3-5; Solvent: THF

Experimental Section

General. All reactions and manipulations were performed under an atmosphere of nitrogen using standard Schlenk techniques. THF was distilled from sodium/benzophenone. GC analyses were performed on a Shimadzu GC-14A equipped with a flame ionization detector using Shimadzu Capillary Column (CBP1-M25-025). The GC yields were determined using suitable hydrocarbon as internal standards. NMR spectra were recorded on a JEOL EX-270 FT NMR spectrometer, GC-MS on Shimadzu GCMS-QP1000EX and high resolution MS on Shimadzu-Kratos CONCEPT IS. Ethylmagnesium bromide (0.96 M THF solution), *n*-butyllithium (1.65 M *n*-hexane solution), *tert*-butyllithium (1.49 M *n*-pentane solution) and *sec*-butyllithium (1.08 M cyclohexane solution) were purchased from Kanto Chemical Co. Inc. Zirconocene dichloride and trimethylphosphine (1.0 M THF solution) were purchased from Aldrich Chemical Company, Inc. Ethyllithium, isobutyllithium and neopentyllithium were prepared from the corresponding alkyl iodide and *tert*-butyllithium in ether.[13] $Cp_2Zr(CH_3)Cl$ was prepared by treatment of $(Cp_2ZrCl)_2O$ with trimethylaluminum according to a literature.[9]

Preparation of $Cp_2Zr(CH_2{=}CH_2)$ (1). To a solution of Cp_2ZrCl_2 (0.29 g, 1.0 mmol) was added ethylmagnesium bromide (0.96 M THF solution, 2.0 mmol) at -78 °C and a mixture was stirred for 1 h. After a dry ice bath was removed, a part of the reaction mixture was transferred to a NMR tube and investigated by NMR study at room temperature. The NMR spectrum showed the formation of unstable species, $Cp_2Zr(CH_2{=}CH_2)$. This species gradually decomposed at room temperature. The build-up to 54% NMR yield of this species was observed. ^1H NMR (THF/C_6D_6, Me_4Si): δ 0.66 (s, 4H), 5.53 (s, 10H). ^{13}C NMR (THF/C_6D_6, Me_4Si): δ 33.64, 104.93.

Reaction of $Cp_2Zr(CH_2{=}CH_2)$ (1) with PMe_3. To a solution of $Cp_2Zr(CH_2{=}CH_2)$ (0.06 mmol) prepared above was added PMe_3 (1.0 M THF solution, 0.3 mmol) at room temperature. After 1h, its NMR spectrum showed the formation of $Cp_2Zr(CH_2{=}CH_2)(PMe_3)$ **4a** in 56% yield (based on Cp_2ZrCl_2).

Reaction of $Cp_2Zr(CH_2{=}CH_2)$ (1) with EtMgBr. This reaction was carried out in a similar manner to the procedure described above. To a solution of $Cp_2Zr(CH_2{=}CH_2)$ (0.06 mmol), ethylmagnesium bromide (0.96 M THF solution, 0.5 mmol) was added at room temperature. After 1h, NMR spectrum showed the formation of $[Cp_2ZrEt(CH_2{=}CH_2)]MgBr$ (**5**) in 42% NMR yield (based on Cp_2ZrCl_2).

Preparation of $[Cp_2ZrEt(CH_2{=}CH_2)]MgBr$ (5). To a solution of Cp_2ZrCl_2 (0.29 g, 1.0 mmol) in THF (5 mL) was added ethylmagnesium bromide (1.0 M THF solution, 3.0 mmol) at -78 °C. After the reaction mixture was stirred for 1h at -78°C, it was warmed up to room temperature. Its NMR spectrum showed the formation of $[Cp_2ZrEt(CH_2{=}CH_2)]MgBr$ (**5**) in 82% yield. ^1H NMR (THF/C_6D_6): δ -0.5 (br, 2H), 0.51 (br, 2H), 5.3 (s, 10H), other

signals overlapped those of solvents. ^{13}C NMR (THF/C_6D_6): δ 103.37 (Cp), other signals were too broad to detect.

Reaction of [$Cp_2ZrEt(CH_2{=}CH_2)$]MgBr (5) with PMe_3. To a solution of [$Cp_2ZrEt(CH_2{=}CH_2)$]MgBr (**3**) prepared as described above was added trimethylphosphine (1.0 M THF solution, 1.0 mmol) at room temperature and the mixture was stirred for 1h. Its ^1H NMR spectrum showed the formation of $Cp_2Zr(CH_2{=}CH_2)(PMe_3)$ (**4a**) in 93% yield along with the recovery of ethylmagnesium bromide (66% yield).

Determination of a Decomposition Rate Constant of $Cp_2Zr(CH_2{=}CH_2)$ (1). The zirconocene-ethylene complex $Cp_2Zr(CH_2{=}CH_2)$ (**1**) was prepared as described above. The decomposition reaction of **1** in THF/C_6D_6 (1/1) was followed by ^1H NMR spectroscopy at 23 °C. Decrease of the Cp signal at 5.53 ppm was used to determine the decomposition rate. The decomposition reaction of **1** obeyed the first order rule and the rate constant was 2.2 x 10^{-4} sec^{-1} (23 °C).

Determination of Decomposition Rate Constants of [$Cp_2ZrEt(CH_2{=}CH_2)$]MgBr (5) in the Presence or Absence of an Excess of EtMgBr. The decomposition reaction of **5** prepared as described above was followed by ^1H NMR spectroscopy at 23 °C. The Cp signal at 5.3 ppm was used to determine the rate constant. The decomposition of **5** obeyed the first order rule and the rate constant was 4.3 x 10^{-5} sec^{-1} (23°C). Decomposition reactions of **5** in the presence of 1 and 5 equiv of EtMgBr were also investigated in a similar way. The rate constant of **5** in the presence of additional 1 equiv of EtMgBr was 1.6 x 10^{-5} sec^{-1} (23°C). In the presence of 5 equiv of EtMgBr, the ate complex **5** was stable enough that 69% of **5** remained after 12 h.

Preparation of $Cp_2ZrMe(CH_2CMe_3)$ (11). To a solution of $Cp_2Zr(CH_3)Cl$ (0.13 g; 0.47 mmol) in THF was added an ether solution of neopentyllithium (0.38 M, 0.47 mmol) at -78 °C and the mixture was stirred for 1h. And then, the reaction mixture was warmed up to room temperature and stirred for additional 1h. The NMR spectra indicated the formation of (**11**) in 80% yield. ^1H NMR (C_6H_6/C_6D_6, Me_4Si): δ -0.10 (s, 3H), 0.47 (s, 2H), 1.04 (s, 9H), 5.89 (s, 10H). ^{13}C NMR (C_6H_6/C_6D_6, Me_4Si): δ 28.14, 35.42 , 37.59, 76.44, 110.28.

Reaction of $Cp_2ZrMe(CH_2CMe_3)$ (11) with EtMgBr in the Presence of PMe_3. To a solution of $Cp_2Zr(Me)(CH_2C(CH_3)_3)$ (0.8 mmol) prepared above was added PMe_3 (1.0 mmol) and EtMgBr (1.0 mmol) at room temperature. After the reaction mixture was stirred for 36 h, ^1H NMR spectra showed the formation of $Cp_2Zr(CH_2{=}CH_2)(PMe_3)$ **4a** (55% yield) along with the formation of neopentylmagnesium (32% yield) bromide and MeMgBr (5% yield). Starting compound **11** was recovered in 45% yield.

Determination of rate constants of β-hydrogen abstraction of $Cp_2Zr(CH_3)R$ (R= CH_2CH_3, $(CH_2)_3CH_3$, $CH_2CH(CH_3)_2$, $C(CH_3)_3$, $CH(CH_3)CH_2CH_3$) in the presence or absence of $P(CH_3)_3$. Typically, to a solution of $Cp_2Zr(CH_3)(CH_2CH_3)$ (0.45 mmol) prepared in situ at -78 °C trimethylphosphine (1.0 M THF solution, 0.5 mL; 0.5 mmol), if

used, was added at -78°C. And then, the reaction mixture (ca. 0.2 mL) was transferred into a 5 mmϕ NMR tube which contains 0.2 ml of benzene-d_6 or toluene-d_8. An NMR probe was regulated to 45 °C, 20 °C or 0 °C, and decrease of a signal for Cp was observed to determine the rate constants. The rate constants of β-hydrogen abstraction of title compounds were as follows. $Cp_2Zr(CH_3)(CH_2CH_3)$: 5.23±7 x 10^{-2} min^{-1} (20 °C) and 0.84±3 x 10^{-2} min^{-1} (0 °C) in the presence of $P(CH_3)_3$, 5.05±8 x 10^{-2} min^{-1} (20 °C) and 0.516±5 x 10^{-2} min^{-1} (0 °C) in the absence of $P(CH_3)_3$, respectively. $Cp_2Zr(CH_3)((CH_2)_3CH_3)$: 0.75±3 x 10^{-2} min^{-1} (20 °C) in the presence of $P(CH_3)_3$ and 0.83±4 x 10^{-2} min^{-1} (20 °C) in the absence of $P(CH_3)_3$, respectively. $Cp_2Zr(CH_3)(CH_2CH(CH_3)_2)$: 1.72±9 x 10^{-2} min^{-1} (45 °C) and 0.17±2 x 10^{-2} min^{-1} (20 °C) in the presence of $P(CH_3)_3$, 1.10±3 x 10^{-2} min^{-1} (45 °C) and 0.19±2 x 10^{-2} min^{-1} (20 °C) in the absence of $P(CH_3)_3$, respectively. $Cp_2Zr(CH_3)(C(CH_3)_3)$: 0.61±1 x 10^{-2} min^{-1} (0 °C) in the presence of $P(CH_3)_3$ and 0.52±2 x 10^{-2} min^{-1} (0 °C) in the absence of $P(CH_3)_3$, respectively.

Bis(η^5-2,4-cyclopentadien-1-yl)ethylmethylzirconium. To a solution of bis(η^5-2,4-cyclopentadien-1-yl)chloromethylzirconium ($Cp_2Zr(CH_3)Cl$) (135 mg; 0.5 mmol) in tetrahydrofuran (2 ml) was added an ether solution of ethyllithium (0.37 M, 1.34 ml; 0.5 mmol) at -78 °C and the mixture was stirred for 1h. The NMR spectra for identification of these species were obtained at -20 °C because they decomposed gradually at higher temperature. Yield of the title compound was determined by ^{1}H NMR (90%). ^{1}H NMR (C_6D_6/THF/ether/pentane, Me_4Si): δ 5.96 (s, 10H, C_5H_5), 0.30 (q, 2H, $ZrCH_2CH_3$, J = 7.8 Hz), -0.30 (s, 3H, $ZrCH_3$), and methyl signal of ethyl group was covered with solvent signals. ^{13}C NMR: δ 110.80, 44.11, 30.12, 16.69.

Bis(η^5-2,4-cyclopentadien-1-yl)butylmethylzirconium. The title compound was prepared in a similar manner to the case of bis(η^5-2,4-cyclopentadien-1-yl)ethylmethylzirconium using *n*-butyllithium instead of ethyllithium. Yield 90%: ^{1}H NMR (C_6D_6/THF/hexane, Me_4Si): δ 5.97 (s, 10H, C_5H_5), 0.35-0.29 (m, 2H, $ZrCH_2(CH_2)_2CH_3$), -0.31 (s, 3H, $ZrCH_3$), and other signals of butyl group were covered with solvent peaks. ^{13}C NMR: δ 110.78, 53.35, 30.26, 30.04, 29.70, 11.82.

Bis(η^5-2,4-cyclopentadien-1-yl)methyl(2-methylpropyl)zirconium. Similar reaction was carried out to prepare the title compound to the above reaction using isobutyllithium. Yield 92%: ^{1}H NMR (C_6D_6/THF/ether/pentane, Me_4Si): δ 5.95 (s, 10H, C_5H_5), 0.21 (d, 2H, $ZrCH_2CH(CH_3)_2$ J = 6.6 Hz), -0.28 (s, 3H, $ZrCH_3$), and other signals of isobutyl group were covered with solvent peaks. ^{13}C NMR: δ 110.65, 66.90, 33.66, 29.11, 28.70.

Bis(η^5-2,4-cyclopentadien-1-yl)(1,1-dimethylethyl)methylzirconium. The title compound was prepared in a similar manner to the above reactions using *tert*-butyllithium. The NMR spectra for identification were obtained at -40 °C. Yield 83%: ^{1}H NMR (C_6D_6/THF/pentane, Me_4Si): δ 5.95 (s, 10H, C_5H_5), 0.96 (s, 9H, $ZrC(CH_3)_3$, -0.16 (s, 3H, $ZrCH_3$). ^{13}C NMR: δ 111.39, 51.72, 34.95, 34.30.

Bis(η^5-2,4-cyclopentadien-1-yl)methyl(1-methylpropyl)zirconium. Similar reaction was carried out to prepare the title compound using *sec*-butyllithium. The NMR spectra for identification were obtained at -40 °C. Yield 65%: ^{1}H NMR (C_6D_6/THF/hexane?, Me_4Si): δ 5.95 (s, 10H, C_5H_5), 0.96 (s, 9H, $ZrC(CH_3)_3$, -0.16 (s, 3H, $ZrCH_3$). ^{13}C NMR: δ 111.39, 51.72, 34.95, 34.30.

Zirconium Catalyzed Reaction of 1-Octene with *n*-OctMgCl. 9-Methyl-6-pentadecene (13d): Representative Procedure. To a solution of Cp_2ZrCl_2 (0.009 g, 0.03 mmol) in THF (2 mL) at -78°C was added dropwise *n*-OctMgCl (2.4 M in THF, 0.42 mL, 1 mmol). After 1h, 1-octene (0.78 mL, 5 mmol) was added to the reaction mixture which was allowed to warm to 25°C and then heated at 60°C for 36h. At this time GLC analysis of a 3N HCl quenched aliquot using a hydrocarbon internal standard indicated a ca. 92% yield of **13d**, based on Mg. The reaction mixture was quenched with 3N HCl, extracted with hexane, washed with $NaHCO_3$, brine and dried over $MgSO_4$. Concentration followed by distillation provided 0.18 g (80%) of the title compound as a ca. 4:1 mixture of trans-**13d** and cis-**13d**, respectively: bp 95°C (1 mmHg, Kugelrohr); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.8-0.95 (m, 9H), 1.05-1.5 (m, 17H), 1.75-2.1 (m, 4H), 5.35-5.45 (m, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.09, 14.12, 19.51 (cis-**13d**:19.61), 22.59, 22.74, 27.12, 29.41, 29.70, 31.44, 32.00, 32.67, 33.24 (cis-**13d**:33.50), 36.61, 40.17, 128.84 (cis-**13d**: 128.45), 131.63 (cis-**13d**: 130.64); IR (neat) 970 (s) 730 (m) cm^{-1}; HRMS calcd for $C_{16}H_{32}$: 224.2504; found: 224.2509.

9-Monodeuteriomethyl-6-pentadecene (15d): The experiment described above was repeated, but this time the reaction mixture was quenched with DCl in D_2O in place of 3N HCl, Concentration, followed by Kugelrohr distillation provided 0.17 g (78%) of a ca. 1:1 mixture of **13d** and **14d**, respectively, both **13d** and **15d** being a 4:1 mixture of the trans and cis isomers, respectively: bp 95°C (1 mm Hg); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.09, 14.12, 18.94, 19.11, 19.45, 22.59, 22.74, 27.12, 29.41, 29.70, 31.44, 32.00, 32.67, 33.14 (cis-**15d**:33.40), 36.61, 40.17, 128.84 (cis-**15d**: 128.45), 131.63 (cis-**15d**: 130.64); IR (neat) 970 (s), 730 (m) cm^{-1}; HRMS calcd for $C_{16}H_{31}D$:225.2582; found: 225.2577.

Reaction of $Cp_2Zr(CH_2{=}CH_2)$ prepared in situ with 2-octene. To a solution of Cp_2ZrCl_2 (0.29 g, 1 mmol) in THF (5 mL) were added sequentially 2.0 mL of EtMgBr in THF (1.0 M, 2.0 mmol) and 2-octene (0.15 mL, 0.11 g, 1 mmol) at -78°C. The reaction mixture was stirred at -78°C and allowed to warm to room temperature. The reaction mixture was quenched with 3N HCl, extracted with hexane, washed with $NaHCO_3$, brine and dried over $MgSO_4$. Concentration provided (*E*)-3-methyl-4-nonene in 36% yield.

Zirconium Catalyzed Reaction of β-Ethylstyrene with EtMgBr: This catalytic reaction was carried out in a similar manner as described above in the Zr catalyzed reaction of EtMgBr with 1-decene. Ethylated product, 3-benzylpentane was obtained in 46% GC yield with >96% regioselectivity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.87 (m, J =7.3 Hz, 6H), 1.29 (dq, J = 7

Hz, 4H), 1.39-1.63 (m, 1H), 2.52 (d, J = 6.9 Hz, 2H), 7.13-7.28 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 10.84, 24.98, 39.75, 42.66, 125.51, 128.08, 129.20, 141.87.

1-Deuterio-2-ethylhexylbenzene: Yield 58% (GC) with >98% regioselectivity. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.83-0.89 (m, 6H), 1.26-1.34 (m, 8H), 1.58-1.54 (m, 1H), 2.50 (t, J = 6.8 Hz 1H), 7.11-7.27 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 10.80, 14.14, 23.09, 25.43, 28.91, 32.36, 39.80 (C_1 in PhCHD-, J_{HD} = 19.6 Hz), 40.18 (C_1 in $PhCH_2$-), 41.08, 125.51, 128.08, 129.20, 141.83

Zirconium Catalyzed Reaction of 1,2-dihydronaphthalene with EtMgBr: This catalytic reaction was carried out in a similar manner as described above in the Zr catalyzed reaction of EtMgBr with 1-decene using 1,2-dihydronaphthalene instead of 1-decene. The product, 2-ethyltetralin, was obtained in 85% GC yield with ≥98% regioselectivity. ^1H NMR($CDCl_3$, Me_4Si): δ 0.96 (t, J = 7.4 Hz, 3H), 1.26-1.42 (m, 3H), 1.51-1.67 (m, 1H), 1.87-1.93 (m, 1H), 2.37 (dd, J = 16.5 Hz, 10.6 Hz, 1H), 2.74-2.86 (m, 3H), 6.99-7.07 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 11.48, 29.22, 29.27, 35.92, 36.03, 125.41, 128.79, 129.13, 136.85, 136.91. High resolution mass spectroscopy; calcd for $C_{12}H_{16}$: 160.1252, found: 160.1251.

2-Ethylindane: Yield 67% (GC) with >99% regioselectivity. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.97 (t, J = 7.4 Hz, 3H), 1.52 (dq, J = 7.3, 7.3 Hz, 2H), 2.27-2.44 (m, 1H), 2.58 (d, ^2J = 15.5 Hz, ^3J = 8.3 Hz), 3.04 (dd, ^2J = 15.3 Hz, ^3J = 7.8 Hz), 7.09-7.20 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 12.7, 28.59, 39.07, 42.01, 124.38, 125.98, 143.68. High resolution mass spectroscopy; calcd for $C_{11}H_{14}$: 146.1096, found: 146.1085.

***trans*-(±)1-Methyl-2-ethylindane:** Yield 63% (GC). ^1H NMR ($CDCl_3$, Me_4Si): δ 0.98 (t, J = 7.4 Hz, 3H), 1.28 (d, J = 6.9 Hz, 3H), 1.35-1.42 (m, 1H), 1.66-1.90 (m, 2H), 2.49 (dd, J =15.5, 9.2 Hz, 1H), 2.75 (qd, J = 7.2, 7.2 Hz, 1H), 3.02 (dd, J = 15.7, 7.8 Hz, 1H), 7.05-7.16 (m, 4H). ^{13}C NMR($CDCl_3$, Me_4Si): δ 12.74, 18.44, 26.94, 37.74, 45.01, 51.00, 123.07, 124.22, 126.13, 142.91, 148.50. High resolution mass spectroscopy; calcd for $C_{11}H_{14}$: 160.12520, found: 160.12484.

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Chapter 3. Zirconium Catalyzed Novel Allylation Reactions

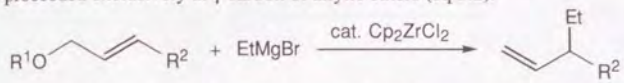
Abstracts: Zirconium catalyzed novel type of regioselective allylation reaction was investigated using allylic ethers and EtMgBr. Mechanistic study indicated that the reaction proceeds via zirconacyclopentanes. The plausible mechanism of the catalytic reaction is proposed. Zirconium catalyzed intramolecular cyclization reactions of unconjugated dienes, which have a terminal double bond and allylic ether moiety, were also investigated as extension of the catalytic allylation. Stereochemistry of the reaction are also discussed.

Introduction

Recently Zr catalyzed C-C bond formation reactions via Zr-alkene complexes have been reported.[1] For allylic compounds, catalytic C-C bond formation using the Cp_2ZrCl_2/EtMgBr system proceeded at β-carbon of allylic compounds.[2] To the best of my knowledge, however, Zr catalyzed allylation reaction (eq 3.1) has not been successful using this system.[3]

(3.1)

Here in this chapter I would like to describe highly selective zirconium catalyzed allylation reactions at γ-carbon of allylic ethers. Treatment of allylic ethers with EtMgBr in the presence of catalytic amount of Cp_2ZrCl_2 gave highly regioselective allylation products. These reactions proceeded exclusively at γ-carbon of allylic ethers (eq 3.2).



(3.2)

In order to extend the allylation reactions, I investigated a catalytic intramolecular cyclization reactions. Intramolecular cyclization reactions using zirconium have been useful for organic synthesis and have been intensively studied.[4] However, zirconium catalyzed intramolecular cyclization is very rare.[5,3a] In this chapter I also describe a zirconium catalyzed or promoted novel type of cyclization reaction.[6,7]

Results and Discussion

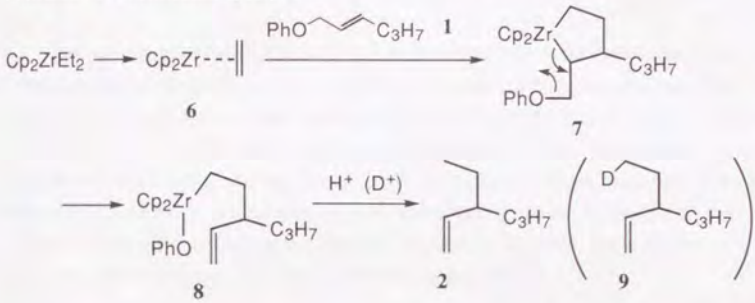
Zirconium Catalyzed Allylation Reaction and Its Mechanistic Consideration

Typical procedure of this catalytic reaction is as follows. To a solution of zirconocene dichloride (29.2 mg; 0.1 mmol) in THF (5 mL) was added THF solution of EtMgBr (0.93 M; 3.0 mmol) at -78 °C and the mixture was stirred for 1 h. After *trans*-2-hexenyl phenyl ether **1** (176 mg; 1.0 mmol) was added, the reaction mixture was allowed to be warmed up to room temperature and stirred for 6 h. The reaction product 3-ethyl-1-hexene **2** was obtained in 70 % yield with >99% regioselectivity. Carbon-carbon bond formation occurred only at γ-carbon of allyl ether **1**. No formation of 4-octene, which was α-attack product, was detected.

Results obtained here are shown in Table 3.1 and the following are noteworthy. First, in the absence of Cp_2ZrCl_2, no desired product was obtained from the mixture of allylic ethers with EtMgBr under conditions used here. The use of MeMgBr instead of EtMgBr in the presence of Cp_2ZrCl_2 did not give the desired product as observed for the other catalytic reactions using zirconocene-alkene complexes. Secondly, Cp_2HfCl_2 could be used for this allylation reaction as a catalyst, although long reaction time was required. Thirdly, carbon-carbon bond formation occurred exclusively at γ-position of allylic ethers and even a trace of α-attacked product could not be detected. Fourthly, the catalytic reactions of 2-hexenyl ethers or 2-cyclopentenyl ethers did not give organomagnesium compounds as products. Treatment of reaction mixtures with

DCl/D_2O gave non-deuterated products (<1% of deuterated product). In the case of the reaction of 2,5-dihydrofuran with 1.2 equiv of EtMgBr, 2-ethyl-3-buten-1-ol was cleanly formed in 65% yield after hydrolysis. However, when 5 equiv of EtMgBr was used, further C-C bond formation occurred to give double ethylation product **5**. Second ethylation is Dzhemilev type of ethylation reaction of terminal double bond of **4**.[2d]

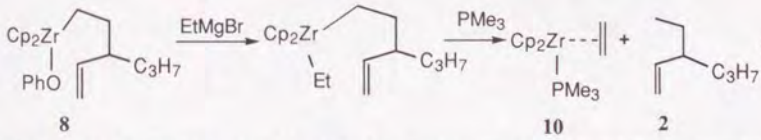
In order to elucidate the mechanism of this catalytic reaction we carried out the following stoichiometric reactions of allylic ethers with Cp_2ZrEt_2 or Cp_2ZrBu_2. Reaction of *trans*-2-hexenyl phenyl ether **1** with 1 equiv of Cp_2ZrEt_2 gave product **2** in 74% yield at room temperature after hydrolysis and deuterolysis gave deuterated product **9** (>98% D incorporated). Formation of intermediate species **8**



(3.3)

was detected by ^1H and ^{13}C NMR (65% yield by ^1H NMR).[8] This species **8** could be also prepared by addition of one equiv of phenol to di(3-propyl-4-pentenyl)zirconocene.[9]

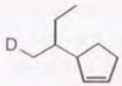
Treatment of **8** with 2 equiv of EtMgBr at room temperature for 1 h liberated the desired product **2** in 71% yield after 1h along with the formation of zirconocene-ethylene complex (or zirconacyclopropane), $Cp_2Zr(CH_2{=}CH_2)(PMe_3)$ **10**.[10] Deuterated product was not obtained after deuterolysis of reaction mixture. On the other hand, addition of **1** to Cp_2ZrBu_2 instead of Cp_2ZrEt_2 did not give any butylated products. Only less bulky substrates such as cyclopentenyl



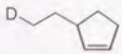
(3.4)

ether afforded butylated product **11** (yield 65%) which was obviously not from the nucleophilic attack by *n*-butyl group but via zirconocene-butene complex. In fact, deuterolysis of the reaction mixture gave **12** (>98% D). Stoichiometric reaction of cyclopentenyl ethers with Cp_2ZrEt_2 gave **13** (>97% D) after deuterolysis as expected.

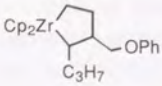
11



12



13

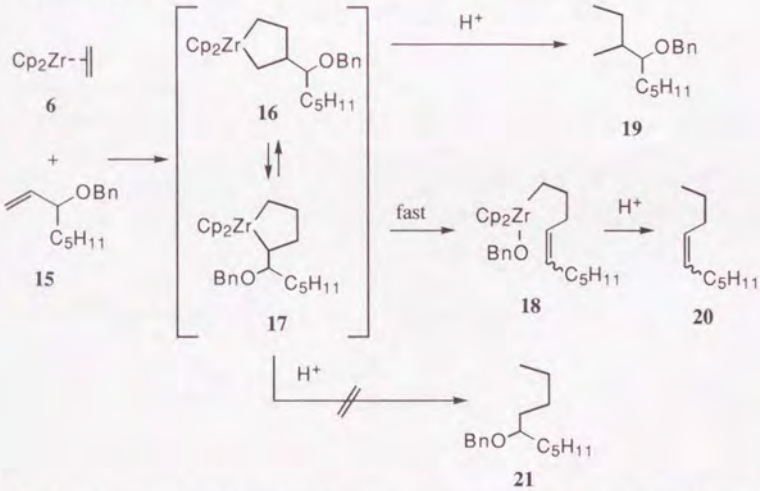


14

It is known that Cp_2ZrEt_2 is converted into zirconocene-ethylene complex.[10b,11] Stabilized zirconocene-ethylene complex with PMe_3 **10** reacted with *trans*-2-hexenyl phenyl ether to give intermediate **8** at 60 °C after 23h and hydrolysis of reaction mixture gave **2** in 57% yield. Cyclopentenyl ether reacted with **10** to give 3-ethylcyclopentene **3** in 71% yield at room temperature after hydrolysis. In addition, treatment of this reaction mixture with 1 equiv of EtMgBr regenerate **10** in 80% yield in the presence of PMe_3 and released product **3** in 78% yield.

Two zirconacyclopentanes **7** and **14** can be considered as zirconacyclopentane intermediates formed by the reaction of **6** with **1**. Unfortunately, these zirconacyclopentanes **7** and **14** were not detected. However, a reaction of Cp_2ZrEt_2 with **15** at -15°C for 2h gave a mixture of **19** and **20** in 66% and 17%, respectively, after hydrolysis. When this reaction mixture was gradually warmed to 0°C and was stirred for 2h, the yields of **19** and **20** became 31% and 45%, respectively. At room temperature, only **20** was obtained in 66% yield after hydrolysis. The product **19** completely disappeared. Cooling the mixture to -15°C again did not give **19** after hydrolysis. During this reaction the product **21** was not detected.

Scheme 3.1



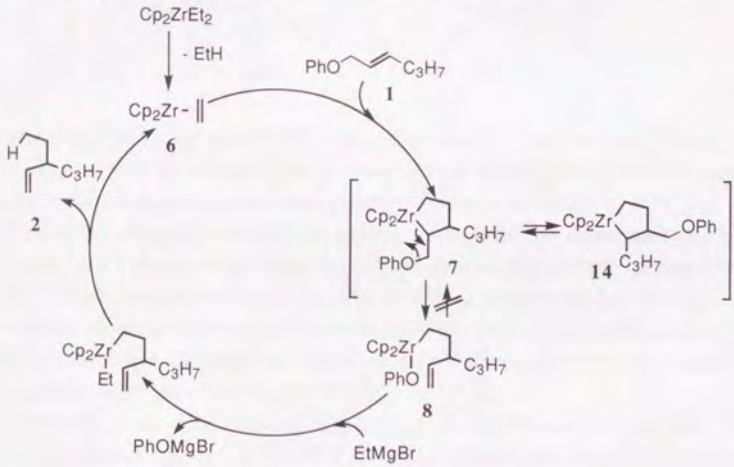
This result suggests that the equilibrium between two regioisomers **16** and **17** exists. And that zirconacyclopentane **17** is converted into **18** very fast by abstraction of OBn group by Zr.

Because hydrolysis of the mixture did not give **21** but **20**. Therefore only **18** was formed at room temperature, even though two regioisomers **16** and **17** were formed as intermediates. This result clearly explains the highly selective C-C bond formation at γ-position of allylic ethers.

These results obtained here strongly suggested the following catalytic reaction mechanism as shown in Figure 3.1. Allylic ether **1** reacts with zirconocene-ethylene complex **6** to produce zirconacyclopentane **7** and its isomer **14**. Sequential C-Zr bond and C-O bond cleavages of **7** afford **8**. Since **7** and its isomer **14** are in equilibrium, the isomer **14** is also converted into **8** via **7**. Alternative route involving the attack of ethylene to γ-carbon of allylic ether and simultaneous C-O bond cleavage without forming zirconacyclopentane intermediate **7** can not be ruled out. This mechanism explains the reason why catalytic allylations proceeded exclusively at γ-position of allylic compounds. Intermediate species **8** easily reacted with EtMgBr to liberate the desired product **2** along with the regeneration of zirconocene-ethylene complex **6** as described above. Oxidative addition product of allylic ether to zirconium (II) species[12] is unlikely as an intermediate. Stoichiometric reaction of allylic ether **1** with Cp_2ZrBu_2[13] did not give the desired product **2** after treatment with EtMgBr.

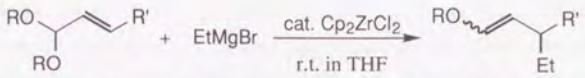
Further investigations on zirconium catalyzed selective reactions using the zirconocene-alkene complex system are now in progress.

Figure 3.1 Proposed Mechanism for The Catalytic Cycle



Catalytic Reactions of α,β-Unsaturated Acetals

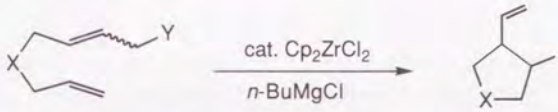
In order to investigate the scope of this catalytic C-C bond formation, I used here α,β-unsaturated acetals which could afford a functionalized allylic moiety in the products.



(3.5)

A catalytic cycle could be developed using EtMgBr (eq 3.5). The results are shown in Table 3.2. The C-C bond formation occurred exclusively at the β-carbon of α,β-unsaturated acetals. A plausible mechanism for this catalytic reaction is the same as that I described above for the reactions of allylic ethers.

Zirconium Catalyzed or Promoted Novel Type of Cyclization Reaction



(3.6)

22a: X = CH_2, Y = OPh, trans
22b: X = CH_2, Y = OMe, trans
23a: X = NPr, Y = OPh, cis
23b: X = NPr, Y = OPh, trans
24a: X = NPh, Y = OPh, cis
24b: X = NPh, Y = OPh, trans

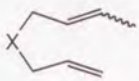
25: X = CH_2
26: X = NPr
27: X = NPh

Mechanistic investigation of the above zirconium catalyzed allylation reaction led me to the idea of intramolecular cyclization allylation. This idea was accomplished using an unconjugated diene **22-24** that contains a terminal double bond and an allyl ether moiety (eq 3.6).

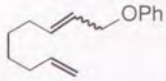
Typical procedure is as follows. To a mixture of zirconocene dichloride (0.059 g, 0.20 mmol) and *trans-N*-phenyl-*N*-allyl-4-phenoxy-2-butenylamine (**24b**) (0.28 g, 1.0 mmol) in THF (0.5 mL) at room temperature was added THF solution of butylmagnesium chloride (1.05 M THF solution, 3 mmol). After stirring for 12 h the reaction mixture was quenched with 3N HCl. Treatment with 30% NaOH and usual work up gave 4-methyl-1-phenyl-3-vinylpyrrolidine (**27**) (74% yield, a mixture of cis:trans isomers 63:37).

Results are shown in Table 3.3. Cyclization products were obtained in good yields. When the resulting mixture was treated with 20% DCl/D_2O, no deuterated products were detected. Elimination products **28**[12] were not formed. Zirconocene complex with butyl substituted cyclopentadienyl ligands, $(C_5H_4Bu)_2ZrCl_2$, gave relatively higher yields than Cp_2ZrCl_2. Catalytic reaction of **29**, however, afforded the desired six-membered product **30** only in low yield.[14] Stoichiometric cyclization reaction of **22-24** with Cp_2ZrBu_2 (Negishi reagent)[13] gave

the cyclization products **25-27**, respectively, in high yields after hydrolysis. Stereochemistry of the cyclized products was not strongly dependent on the structure of their starting materials. Interestingly, however, the cis:trans ratio of the products was dependent on the amount of Cp_2ZrBu_2 and a reaction time. First, the cis:trans ratio dramatically changed, for example, from 74:26 to 10:90 for **24b** when an excess of Cp_2ZrBu_2 was used. Secondly, the reaction of **24a** with 1.2 equiv of Cp_2ZrBu_2 gave **27** after hydrolysis in a ratio of 44:56 after 1h. However, a longer reaction time (3 h) led to the ratio of 17:83. The stereoisomerization reaction must occur after cyclization reactions. Third, when **23b** was treated with 1.1 equiv of zirconium complex with dimethylated cyclopentadienyl rings, $(C_5H_3Me_2)ZrBu_2$, the product **5** was formed in 94% yield (cis:trans = 92:8). However, an excess of $(C_5H_3Me_2)ZrBu_2$ does not lead to the stereoisomerization. This is in contrast to the reaction with Cp_2ZrBu_2.



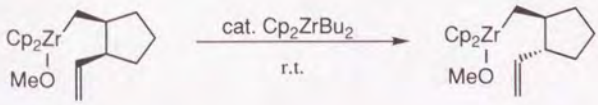
28



29

30

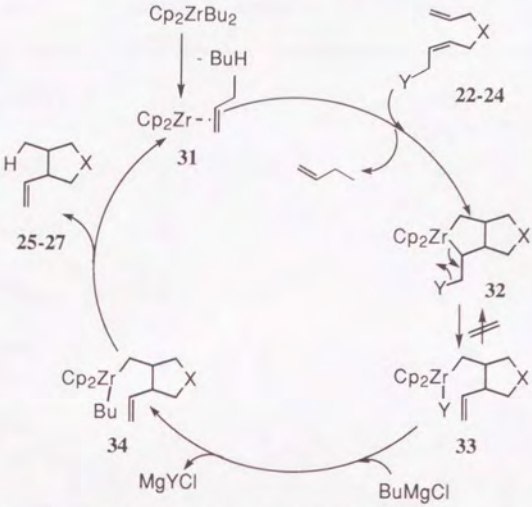
Zirconium containing stoichiometric reaction product **33** was spectroscopically characterized. The ^1H NMR spectrum of trans isomer of **33b** (X = CH_2; Y = OMe) showed two singlets at 5.72 and 5.77 ppm assignable to Cp protons and one methyl signal of OMe group at 3.67 ppm. The ^{13}C NMR also indicated two resonances at 110.30 and 110.53 ppm assigned to Cp carbons and one methyl group of OMe at 61.63ppm. Similar type of zirconocene complex prepared from zirconocene-ethylene complex and allylic ethers has been characterized by the investigation described above. A reaction of **33b** (X = CH_2; Y = OMe, cis: trans = 47 : 53) with a catalytic amount of Cp_2ZrBu_2 was monitored by ^1H NMR spectroscopy. Interestingly, the stereoisomerization reaction of **33b** (cis isomer) occurred to give its trans isomer (eq 2; cis:trans = 4:96; at room temperature for 30 min). Total amount of cis and trans isomers was constant during the reaction. Treatment of cyclization product **27** (cis:trans = 74:26) with 5 mol% of Cp_2ZrBu_2 also showed similar isomerization to give predominantly the trans isomer (cis:trans = 13:87, 95% yield) after 8h. Although we must await further investigations to elucidate the mechanism of this stereoisomerization reaction, the reaction possibly involves abstraction of allylic hydrogen by a Zr(II) species. Lewis acid catalyzed mechanism cannot be ruled out. In catalytic reactions, since only small amount of zirconocene complex was used, this type of isomerization does not affect the cis:trans ratio.



(3.7)

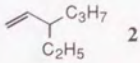
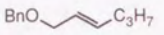
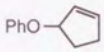
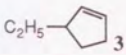
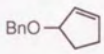
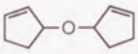
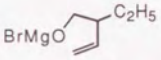
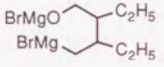
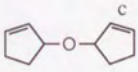
33b: cis **33b**: trans

Figure 3.2 Proposed Mechanism for The Catalytic Cyclization



A plausible mechanism for the catalytic cyclization reaction (Figure 3.2) involves (i) the replacement of butene on zirconium by **22-24**, (ii) a bicyclization and a sequential elimination of alkoxy group[15,3a-b] from **32** to form **33**, (iii) transmetalation by BuMgCl and (iv) a β-hydrogen abstraction from a Bu group on zirconium to regenerate the zirconocene-butene complex **31**. Actually a reaction of **33b** (X = CH_2; Y = OMe) with 1.2 equiv of BuMgCl in the presence of PMe_3 gave the butene complex stabilized with PMe_3 in 76% yield. β-Hydrogen abstraction from a Bu group in **34** was more favorable than that from the cyclized moiety.[16]

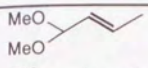
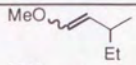
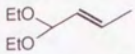
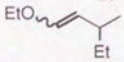
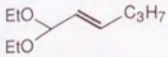
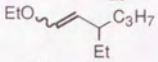
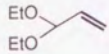
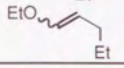
Table 3.1 Zirconium Catalyzed C-C Bond Forming Reaction of Allylic Ethers.[a]

substrate	EtMgBr (n equiv)	time/h	product	yield/%
 **1**	3	6	 **2**	70
	3	6	**2**	50
	3	6	**2**	60
	2	6[b]	**2**	51
	2	6	 **3**	75
	3	6	**3**	76
	2	6	**3**	77
	1.2	1	 **4**	65
	5	48	 **5**	53
 c	2	65	**3**	65

a) Reaction conditions; Cp_2ZrCl_2: Allylic ether = 0.1 : 1; room temperature in THF.

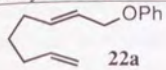
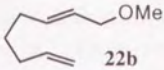
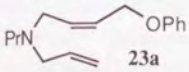
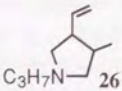
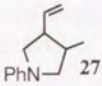
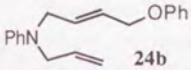
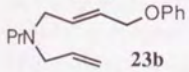
b) 50°C for 6h after stirring at r.t. for 6h. c) Cp_2HfCl_2 was used as a catalyst.

Table 3.2 Zirconium Catalyzed C-C Bond Formation of α,β-Unsaturated Acetals with EtMgBr

Substrate	Equiv of EtMgBr	Time /h	Product	Yield /%	trans:cis
	2	24		81	66:34
	2	24		79	75:25
	2	6		61	78:22
	2	24		30	69:31

a) Conditions: Cp_2ZrCl_2:Acetals = 0.1:1; room temperature in THF.

Table 3.3 Zirconium Catalyzed or Promoted Novel Type of Cyclization Reactions

substrate	catalyst system or reagent	temp/ ℃	time /h	product	yield[c] /%	cis/tr ratio
Catalytic Reaction	n eq Cp_2ZrCl_2[a]					
 **22a**	0.1	r.t.	24	 **25**	63	38:62
	0.2[b]	r.t.	12		84	39:61
 **22b**	0.2	r.t.	3	**25**	68	31:69
 **23a**	0.2	50	3	 **26**	59	24:76
 **24a**	0.2	r.t.	12	 **27**	61	42:58
		r.t.	24		61	45:55
	0.2[b]	r.t.	24		78	44:56
 **24b**	0.2	r.t.	12	**27**	74	63:37
Stoichiometric Reaction	n eq Cp_2ZrBu_2					
22a	1.2	r.t.	12	**25**	>98	28:72
22b	1.2	r.t.	6	**25**	89	8:92
23a	1.1	r.t.	6	**26**	97	33:67
 **23b**	1.1	r.t.	6	**26**	>98	74:26
	1.1[d]	r.t.	6		94	92:8
24a	1.2	r.t.	1	**27**	96	44:56
	1.2	r.t.	3		72	17:83
24b	1.0	r.t.	6	**27**	78	74:26
	1.5	r.t.	6		50	10:90

[a]The catalytic reaction was carried out in the presence of n eq of Cp_2ZrCl_2 and 3.0 eq of n-BuMgCl in THF. [b]$(C_5H_4Bu)_2ZrCl_2$ was used as a catalyst instead of Cp_2ZrCl_2. [c]Combined yield of cis and trans isomers. For stoichiometric reactions, products were obtained after hydrolysis. [d]$(C_5H_3Me_2)_2ZrBu_2$ was used as a reagent instead of Cp_2ZrBu_2.

Experimental Section

General. All reactions were carried out under an nitrogen atmosphere. Teterahydrofuran was dried over sodium and distilled. Zirconocene dichloride and cyclopentenyl ether were purchased from Aldrich Chemical Company, Inc. Allyl phenyl ether and 2,5-dihydrofuran were purchased from Wako Pure Chemical Industries, Ltd. Other allylic ethers were prepared in usual method. Ethylmagnesium bromide (1.05 M THF solution), butylmagnesium chloride (1.05 M THF solution) and *n*-butyllithium (1.64 M hexane solution) were purchased from Kanto Chemical Co. Inc. Zirconium complexes, $(C_5H_4Bu)_2ZrCl_2$ and $(C_5H_3Me_2)ZrBu_2$, were provided by Kanto Chemical Co. Inc. Compounds **22a** and **22b** were prepared by the method in a literature.[17] Compounds **23** and **24** were prepared by the reaction of 4-chloro-2-butyl phenyl ether with allylpropylamine and allylphenylamine, respectively. NMR spectra were recorded on a JEOL EX-270 FT NMR spectrometer, GC-MS on Shimadzu GCMS-QP1000EX and high resolution MS on Shimadzu-KRATOS CONCEPT IS. Deuterium incorporation was determined by ^{13}C NMR spectra (gated decoupling pulse technique without NOE).

Zirconium Catalyzed C-C Bond Forming Reaction of Allylic Ethers. Typical procedure of catalytic reaction is as follows. To a solution of zirconocene dichloride (29.2 mg; 0.1 mmol) in THF (5 mL) was added THF solution of ethylmagnesium bromide (0.93 M; 3.0 mmol) at -78 °C and the mixture was stirred for 1 h. After *trans*-2-hexenyl phenyl ether **1** (176 mg; 1.0 mmol) was added, the reaction mixture was allowed to be warmed up to room temperature and stirred for 6 h. The reaction mixture was quenched with 3 N HCl and extracted to ether, and usual workup gave 3-ethyl-1-hexene **2** (70 % yield). Yield was determined by gas chromatography. All products were characterized by ^1H and ^{13}C NMR, GC-MS and high resolution mass spectroscopy.

3-Ethyl-1-hexene (2). ^1H NMR ($CDCl_3$, Me_4Si): δ 0.8-0.9 (m, 6H), 1.1-1.5 (m, 6H), 1.8-1.9 (m, 1H), 4.8-5.0 (m, 2H), 5.4-5.6 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 11.64, 14.20, 20.31, 27.73, 36.96, 45.61, 114.00, 143.36. MS (EI) *m/e* 112 (M^+). High resolution mass spectroscopy; calcd for C_8H_{16}: 112.12520, found: 112.12532.

3-Ethylcyclopentene (3). ^1H NMR (C_6D_6, Me_4Si): δ 0.86 (t, 3H, J = 7.4 Hz), 1.2-1.5 (m, 3H), 1.9-2.1 (m, 1H), 2.2-2.3 (m, 2H), 2.5-2.6 (m, 1H), 5.66-5.71 (m, 2H). ^{13}C NMR (C_6D_6, Me_4Si): δ 12.31, 29.11, 29.74, 32.36, 47.67, 130.38, 135.25. MS (EI) *m/e* 96 (M^+). High resolution mass spectroscopy; calcd for C_7H_{12}: 96.09390, found: 96.09387.

2-Ethyl-3-buten-1-ol. ^1H NMR (C_6D_6, Me_4Si): δ 0.79 (t, 3H, J = 7.4 Hz), 0.86 (s, 1H), 1.0-1.4 (m, 2H), 1.8-2.0 (m, 1H), 3.2-3.4 (m, 2H), 4.9-5.0 (m, 2H), 5.3-5.5 (m, 1H). ^{13}C NMR (C_6D_6, Me_4Si): δ 11.70, 23.76, 48.93, 65.50, 116.64, 140.23. MS (EI) *m/e* 100 (M^+).

2-Ethyl-3-methylpentan-1-ol. (as a ca.1/1 mixture of *meso/racemi*) ^{13}C NMR (C_6D_6, Me_4Si): δ 12.21, 12.26, 12.28, 12.65, 15.15, 15.62, 19.73, 21.33, 26.78, 26.96, 34.47, 34.73, 46.82, 46.88, 62.89, 63.40.

Stoichiometric Reaction of Allylic Ethers with Cp_2ZrR_2 (R = Bu, Et). Typical procedure of stoichiometric reaction is as follows. To a solution of zirconocene dichloride (292 mg; 1.0 mmol) in THF (5 mL) was added THF solution of ethylmagnesium bromide (0.93 M; 2.0 mmol) at -78 °C and the mixture was stirred for 1 h. After cyclopentenyl ether (150 mg; 1.0 mmol) was added, the reaction mixture was allowed to be warmed up to room temperature and stirred for 6 h. The reaction mixture was quenched with 3 N HCl and extracted to ether and usual workup gave 3-(1-methylpropyl)cyclopentene **11** (65 % yield). Yield was determined by gas chromatography. All products were characterized by ^1H and ^{13}C NMR, GC-MS and high resolution mass spectroscopy.

3-(1-Methylpropyl)cyclopentene (11). ^1H NMR (C_6D_6, Me_4Si): δ 0.8-0.9 (m, 6H), 1.0-1.5 (m, 4H), 1.8-2.0 (m, 1H), 2.1-2.3 (m, 2H), 2.5-2.6 (m, 1H), 5.6-5.8 (m, 2H) ^{13}C NMR (C_6D_6, Me_4Si): δ 12.00, 16.62, 27.69, 27.87, 32.61, 39.75, 51.59, 131.07, 133.40. MS (EI) *m/e* 124 (M^+). High resolution mass spectroscopy ; calcd for C_9H_{16}: 124.12520 found: 124.12486.

Alternate Preparation of Intermediate Species (8).

3-(2-Iodoethyl)-1-hexene. To a solution of zirconocene dichloride (2.92 g; 10 mmol) in THF (35 ml) was added THF solution of ethylmagnesium bromide (1.04 M; 20 mmol) at -78 C and the mixture was stirred for 1 h. After *trans*-2-hexenyl phenyl ether **1** (1.76 g; 10 mmol) was added the reaction mixture was allowed to warm up to room temperature and stirred for 24 h. Then iodine (2.54 g, 10 mmol) was added and after 1 h stirring reaction mixture was quenched with 3 N HCl, extracted to the ether and usual workup gave title compound (1.57 g, 62 % yield). ^1H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, 3H, J = 7.0 Hz), 1.20-1.43 (m, 4H), 1.54-1.78 (m, 1H), 1.86-1.99 (m, 1H), 2.06-2.13 (m, 1H), 3.02-3.11 (m, 1H), 3.18-3.29(m, 1H), 5.03-5.09 (m, 2H), 5.37-5.51 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 5.34, 14.03, 20.11, 36.77, 38.45, 44.60, 115.81, 141.13. High resolution mass spectroscopy; calcd for $C_8H_{15}I$: 238.02185 found: 238.02235.

Preparation of Intermediate Species (8). To a suspension of magnesium turnings (3 mmol) in 10 ml THF 3-(2-iodoethyl)-1-hexene (0.714 g, 3 mmol) was added dropwise within 1 hr under stirring and ultrasound irradiation. Reaction mixture was stirred for 12 hr. Transparent solution above precipitate showed 0.11 M concentration of 3-propyl-4-pentenylmagnesium iodide by NMR. To a solution of zirconocene dichloride (73 mg; 0.25 mmol) in THF (1 ml) was added THF solution of 3-propyl-4-pentenylmagnesium iodide (0.11 M; 0.5 mmol) at 0 °C and the mixture was stirred for 1 h. Then phenol (24 mg, 0.25 mmol) was added and reaction mixture was stirred at room temperature for 12 h. NMR spectra showed the formation of **8** in 75% yield. ^1H NMR (C_6D_6/THF, Me_4Si): δ 0.8-1.0 (m, 5H), 1.2-1.9 (m, 7H), 4.9-5.1 (m, 2H), 5.6-5.8

(m, 1H), 6.04 (s, 10H), 6.47 (d, J = 8.2 Hz, 2H), 6.7-6.8 (m, 1H), 7.09 (t, J = 7.8 Hz, 2H). ^{13}C NMR (C_6D_6/THF, Me_4Si): δ 14.66, 21.28, 37.23, 39.51, 40.70, 50.58, 111.70, 113.78, 118.40, 119.37, 129.58, 145.01, 165.69.

Reaction of $Cp_2Zr(CH_2{=}CH_2)(P(CH_3)_3)$ (10) with Allylic Ethers. Typical procedure of the reaction is as follows. To a solution of zirconocene dichloride (292 mg; 1.0 mmol) in THF (2.5 mL) was added THF solution of ethylmagnesium bromide (0.93 M; 2.0 mmol) at -78 °C and the mixture was stirred for 1 h. After THF solution of trimethylphosphine (1.0 M; 1.1 mmol) was added, the reaction mixture was allowed to be warmed up to room temperature and stirred for 3 h. At this time ^1H NMR spectrum of reaction mixture showed formation of **10** in 86% yield. Then cyclopentenyl ether (150 mg; 1.0 mmol) was added and the reaction mixture was stirred for 19 h. At this time ^1H NMR spectrum of reaction mixture showed disappearance of **10** (< 2%). Quenching a portion of reaction mixture with 3 N HCl, extraction to ether and usual workup revealed formation of 3-ethylcyclopentene **3** in 71% yield by GC. Deuterolysis with 20% DCl/D_2O showed only monodeuterated 3-ethyl-cyclopentene **13** (M^+ = 97) by GC-MS. Then THF solution of ethylmagnesium bromide (0.93 M; 1.0 mmol) was added dropwise and the mixture was stirred for 12 h. At this time ^1H NMR spectrum of reaction mixture showed formation of **10** in 80% yield. Quenching of reaction mixture sample with 20% DCl/D_2O showed only nondeuterated 3-ethyl-cyclopentene **3** (M^+ = 96) by GC-MS. The reaction mixture was quenched with 3 N HCl and extracted to ether and usual workup gave 3-ethylcyclopentene in 78% yield by GC.

Reaction of Cp_2ZrEt_2 with benzyl 3-(1-octenyl) ether. Typical procedure is as follows. To a suspension of Cp_2ZrCl_2 (1.25 mmol) in THF (1 mL) was added EtMgBr (0.90 M THF solution; 2.5 mmol) at -78 °C and was stirred for 0.5 h. The reaction mixture was warmed up to -15° C and stirred for 0.5 h. Afterwards benzyl 3-(1-octenyl) ether (1.0 mmol) was added and reaction mixture was stirred at -15° C for 2 h. Quenching a portion of reaction mixture with 3 N HCl, extraction to ether and usual workup revealed formation of benzyl 4-(2-methyl-nonyl) ether (**19**) in 66% yield by GC along with formation of 4-decene (**20**) in 17% yield by GC. Reaction mixture was warmed up to 0° C and stirred for 2 h. Quenching a portion of reaction mixture with 3 N HCl, extraction to ether and usual workup revealed that yields of **19** and **20** became 31% and 45% by GC, respectively. The reaction mixture was warmed up to room temperature and stirred for 3 h. Quenching a portion of reaction mixture with 3 N HCl, extraction to ether and usual workup revealed that yield of **20** became 66% by GC and **19** disappeared - <1% (see the table below).

Benzyl 4-(2-methyl-nonyl) ether (19) (mixture of diastereomers 1:4.4 ratio): ^1H NMR ($CDCl_3$, Me_4Si): δ 0.85-0.95(m, 9H), 1.05-1.75(m, 11H), 3.18-3.27(m, 1H), 4.40-4.53(s, 2H), 7.14-7.38(m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 11.93, 12.02, 14.00, 14.09, 14.49, 22.63, 25.16, 25.45, 25.53, 25.68, 29.58, 30.53, 32.06, 36.91, 37.50, 71.27, 71.65, 82.84, 83.02, 127.15, 127.51, 127.62, 128.10, 139.32. MS (EI) *m/e* 248 (M^+).

4-Decene (20) (mixture cis- and trans-isomers - 4.1:1): ^{1}H NMR (C_6D_6, Me_4Si): δ 0.8-1.0 (m, 6H), 1.2-1.4 (m,8 H), 1.9-2.1 (m, 4H), 5.4-5.5 (m, 2H) ^{13}C NMR (C_6D_6, Me_4Si): δ 13.84, 13.96, 14.29, 22.98, 23.16, 23.29, 27.62, 29.67, 29.79, 29.88, 31.81, 31.90, 33.08, 35.17, 129.88, 130.40, 130.96 MS (EI) *m/e* 140 (M^+).

time	temp/°C	yield of **19**	yield of **20**
15 min	-15	37	6.8
30 min	-15	60	10
2 hr	-15	66	17
1 hr	0	44	35
2 hr	0	31	45
1 hr	r.t.(23)	7	59
3 hr	r.t.(23)	<1	66

^{1}H NMR of intermediate; (C_6D_6/THF, Me_4Si): δ 0.8-1.0 (m, 5H), 1.2-1.9 (m, 7H), 4.9-5.1 (m, 2H), 5.6-5.8 (m, 1H), 6.04 (s, 10H), 6.47 (d, 2H, J = 8.2 Hz), 6.7-6.8 (m, 1H), 7.09(t, 2H, J=7.8Hz).

Zirconium Catalyzed Cyclization. Typical procedure s as follows. To a solution of zirconocene dichloride (58.6 mg; 0.2 mmol) and *trans-N*-phenyl-*N*-allyl-4-phenoxy-2-butenylamine (**24b**) (0.28 g, 1 mmol) in THF (0.5 mL) at room temperature was added THF solution of butylmagnesium chloride (1.05 M THF solution, 3 mmol). After stirring for 12 hours reaction mixture was quenched with 3 N HCl. Treatment with 30% NaOH and usual workup gave 4-methyl-1-phenyl-3-vinylpyrrolidine (**27**) (74 % yield, mixture of cis:trans isomers 63:37). Yield was determined by gas chromatography. All products were characterized by ^{1}H and ^{13}C NMR, GC-MS and high resolution mass spectroscopy. The stereochemistry of *trans* and *cis*-2-methyl-1-vinylcyclopentane (**25**) were determined by NMR spectra comparing with the data in a literature.[18]

Stoichiometric Cyclization Reaction Mediated by Cp_2ZrBu_2. Typical procedure of a stoichiometric reaction is as follows. To a solution of zirconocene dichloride (310 mg; 1.06 mmol) in THF (3.5 mL) was added butyllithium (1.63 M hexane solution, 2.12 mmol) at -78 °C and the mixture was stirred for 1 h. After *cis-N*-phenyl-*N*-allyl-4-phenoxy-2-butenylamine (**24a**) (0.28 g, 1 mmol) was added, the reaction mixture was allowed to warmed up to room temperature and stirred for 6 h. Treatment with 30% NaOH and usual workup gave **27** (98 % yield, mixture of cis:trans isomers 48:52). Yield was determined by gas chromatography. All products were characterized by ^{1}H and ^{13}C NMR, GC-MS and high resolution mass spectroscopy.

***trans*-4-Methyl-1-propyl-3-vinylpyrrolidine** (**26:** trans isomer). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.90 (t, *J* = 7.6 Hz, 3H), 1.01 (d, *J* = 6.6 Hz, 3H), 1.44-1.60 (m, 2H), 1.88-2.03 (m, 1H), 2.17-2.49 (m, 5H), 2.72-2.86 (m, 2H), 4.90-5.10 (m, 2H), 5.68-5.86 (m, 1H). ^{13}C

NMR ($CDCl_3$, Me_4Si): δ 12.06, 17.86, 22.10, 39.08, 51.16, 58.98, 60.25, 62.03, 114.18, 140.88. MS (EI) *m/e* 153 (M^+). High resolution mass spectroscopy; calcd for $C_{10}H_{19}N$: 153.1518, found: 153.1518.

***cis*-4-Methyl-1-propyl-3-vinylpyrrolidine (26:** cis isomer). ^1H NMR ($CDCl_3$, Me_4Si): δ 0.85-0.98 (m, 6H), 1.45-1.60 (m, 2H), 1.90-2.06 (m, 1H), 2.10-2.40 (m, 4H), 2.80-2.95 (m, 1H), 3.00-3.12 (m, 2H), 4.85-5.15 (m, 2H), 5.70-5.90 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 12.06, 15.60, 22.10, 35.29, 45.59, 58.94, 59.73, 62.48, 115.07, 138.79. MS (EI) *m/e* 153 (M^+).

***trans*-4-Methyl-1-phenyl-3-vinylpyrrolidine (27:** trans isomer). ^1H NMR ($CDCl_3$, Me_4Si): δ 1.07 (d, J = 6.6 Hz, 3H), 1.99-2.16 (m, 1H), 2.33-2.46 (m, 1H), 2.91 (dd, J = 9.2 Hz, J = 9.2 Hz, 1H), 3.12 (dd, J = 9.2 Hz, J=9.2 Hz, 1H), 3.45-3.58 (m, 2H), 5.06-5.18 (m, 2H), 5.65-5.82 (m, 1H), 6.50 (d, J = 7.9 Hz, 2H), 6.64 (t, J = 7.3 Hz, 1H), 7.21 (t, J = 8.4 Hz, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 15.89, 38.92, 50.89, 53.26, 54.99, 111.18, 115.34, 116.40, 129.11, 138.43, 147.47. MS (EI) *m/e* 187 (M^+).

***cis*-4-Methyl-1-phenyl-3-vinylpyrrolidine (27:** cis isomer). ^1H NMR ($CDCl_3$, Me_4Si): δ 0.99 (d, J=6.9 Hz, 3H), 2.40-2.51 (m, 1H), 2.82-2.92 (m, 1H), 3.01 (dd, J = 8.9 Hz, J = 5.9 Hz, 1H), 3.24 (dd, J = 9.6 Hz, J = 5.5 Hz, 1H), 3.37-3.47 (m, 2H), 5.02-5.20 (m, 2H), 5.74-5.92 (m, 1H), 6.51 (d, J = 7.6 Hz, 2H), 6.64 (t, J = 7.3 Hz, 1H), 7.21 (t, J = 8.9 Hz, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.39, 36.55, 46.47, 51.72, 54.16, 111.23, 115.25, 116.08, 129.13, 137.03, 147.71. MS (EI) *m/e* 187 (M^+). High resolution mass spectroscopy; calcd for $C_{13}H_{17}N$: 187.1361, found: 187.1355.

Preparation of Intermediate 33b (X = CH_2, Y = OMe, a mixture of cis and trans isomers) **and Its Conversion to Zirconocene-Butene Complex (31).** To a solution of zirconocene dichloride (0.29 g; 1.0 mmol) in THF (3.5 mL) was added butyllithium (1.63 M hexane solution, 2.0 mmol) at -78 °C and the mixture was stirred for 1 h. After *trans*-1-methoxy-2,7-octadiene (0.17 g, 1.2 mmol) was added, the reaction mixture was allowed to warmed up to room temperature and stirred for 3 h. Quenching a portion of reaction mixture with 3 N HCl, extraction to ether and usual workup revealed that yield of 2-methyl-1-vinylcyclopentane (47:53 cis:trans mixture) was 97% by GC. Solvent was removed and residue was dissolved in C_6D_6. NMR showed a clean formation of **33b**. Sample of the solution containing 0.32 mmol of **33b** was placed to the NMR tube and treated at room temperature with PMe_3 (1.0 M in THF, 0.35 mmol) and butylmagnesium chloride (1.05 M THF solution, 0.38 mmol).Reaction was monitored by NMR. After 6 hours at room temperature zirconocene-butene complex stabilized with trimethylphosphine (**31**) was found to be formed in 76% yield.

Isomerization of intermediate 33b. Sample of the **33b** solution prepared as described below (0.30 mmol, cis:trans 47:53) was placed to the NMR tube and treated with Negishi reagent solution (0.015 mmol). Reaction was monitored by NMR. After 30 minutes at

room temperature isomerization was completed. NMR showed that cis isomer was quantitatively isomerized to trans isomer (0.30 mmol, cis:trans 4:96).

Intermediate 33b (trans isomer 96%): ^{1}H NMR (C_6D_6, Me_4Si): δ 0.9-1.2 (m, 3H), 1.5-2.1 (m, 7H), 3.67 (s, 3H), 5.09-5.25 (m, 2H), 5.72 (s, 5H), 5.77 (s, 5H), 5.8-6.1 (m, 1H). ^{13}C NMR (C_6D_6, Me_4Si): δ 23.85, 32.78, 35.81, 44.26, 51.48, 57.83, 61.63, 110.17, 110.58, 113.19, 144.24.

Isomerization of 27. A THF solution of Cp_2ZrBu_2 (0.5 mL, 0.1 mmol), which was prepared with Cp_2ZrCl_2 and *n*-butyllithium at -78°C, was transferred to a solution of **27** (1 mmol, cis:trans=74:26) in benzene (1 mL). The reaction mixture was stirred at room temperature and isomerization was observed by GC. After 8h, the ratio of cis:trans was 13:87 and combined yield of **27** was 95%.

References and Notes

1 see chapter 1, references therein.

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Chapter 4. Novel Type of Carbozirconation Reactions of Alkynes

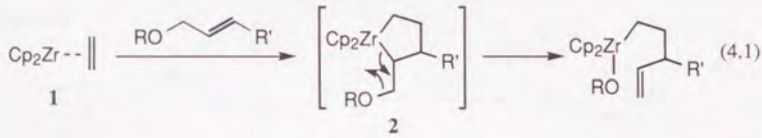
Abstract: Novel type of carbozirconation reaction of alkynes is reported. Treatment of zirconocene-alkyne complexes, zirconacyclopentenes, or zirconacyclopentadienes with allylic compounds gave allylzirconation products of alkynes. Carbozirconation of alkynes with zirconacyclopentenes or zirconacyclopentadienes involved β,β'-C-C bond cleavage reaction of zirconacycles. Reactions of zirconacyclopentenes with homoallyl bromides afforded allylcyclopropane derivatives as carbozirconation products. Vinylzirconation are also accomplished using vinyl ethers or vinyl halides.

Introduction

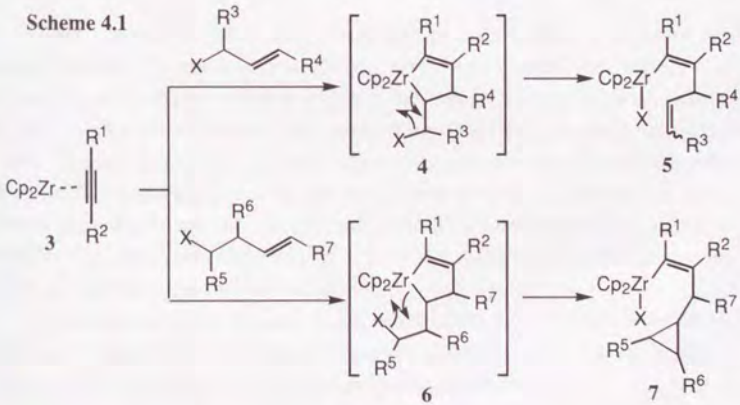
Carbometalation of unsaturated hydrocarbons is an attractive reaction from the viewpoint of synthetic application of organometallic chemistry.[1] Although allylmetalation of alkynes is a valuable reaction among them, only allylmetals containing Li, Mg, B, Zn or Al have been used.[1,2] In addition, the allylmetalation with such allylmetals always involves a problem of regioselectivity. The formation of a new C-C bond can take place at the α- or γ-carbon of an allylic moiety. This regioselectivity depends on its mechanism, and the reactions often give a mixture of two isomers.

On the other hand, zirconium mediated allylzincation of alkynes[3] or zirconium catalyzed allylalumination[4] has been reported by Negishi. However, allylzirconocene compounds, which are easily prepared by the reaction of Cp_2ZrCl_2 with allyl Grignard[5] or by the oxidative addition of allylic ethers to a 'zirconocene equivalent'[6,7,8] (Cp_2ZrBu_2: Negishi reagent), are inert for the allylzirconation of alkynes.

Recently the author and co-workers found that the zirconium-ethylene complex **1** reacted with an allylic ether to afford the allylzirconation product of ethylene.[9] Furthermore, this reaction could be catalytic as an allylation reaction in the presence of EtMgBr. The reaction proceeded via a five membered zirconacyclopentane intermediate **2**, and elimination of the β-alkoxy group from **2** was the key step (eq 4.1).

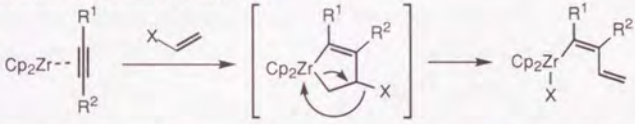


Scheme 4.1



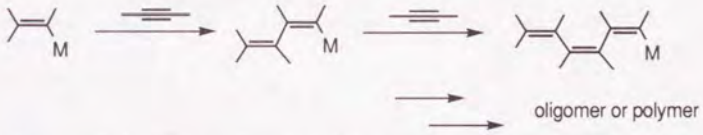
This information led the author to the idea that a similar reaction may also proceed with a combination of usual alkynes and the zirconocene such as **3**. Coupling of alkynes on zirconium with allylic compounds would give zirconacyclopentenes **4** that have a substituent at the α-carbon of the zirconacycles with a leaving group at the β-position. β-Elimination of the leaving group from **4** resulted in the allylated product **5** (Scheme 4.1). Furthermore, I have investigated the possibility of γ-elimination from zirconacyclopentenes **6** which would give **7** involving the formation of a cyclopropane ring.

In this chapter I describe this novel type of carbozirconation of alkynes which involves elimination reactions from α-substituents of zirconacyclopentene derivatives. In addition similar elimination from *β-substituents* were also investigated. This result provided a novel method for vinylzirconation reaction (eq 4.2).



(4.2)

Generally, alkenylmetalation products of alkynes have a similar reactivity to the starting organometallic compounds. This type of carbometalation results in oligomerization or polymerization reactions. This is one of the major reasons to limit the scope of alkenylmetalation of alkynes.[1]



Under controlled conditions alkenylmetalation products of alkynes could be obtained in the case of aluminum[10] or copper.[2,11] However, in these reactions two same alkynes were inserted into an alkyl-aluminum or -copper bond. Since the initiation of these reactions is the insertion of alkyne into alkyl-metal bond, fundamentally, this method does not provide a vinylmetalation product. On the other hand vinylcopper reagent does not react with alkynes. When an activated alkyne such as propargylic alcohol was used, vinylmagnesium chloride could react to give a vinylmetalation product. However, unactivated alkynes do not react with vinylmagnesium chloride. Therefore, surprisingly, there is no procedure to provide vinylmetalation compounds of unactivated alkynes, to the best of my knowledge.

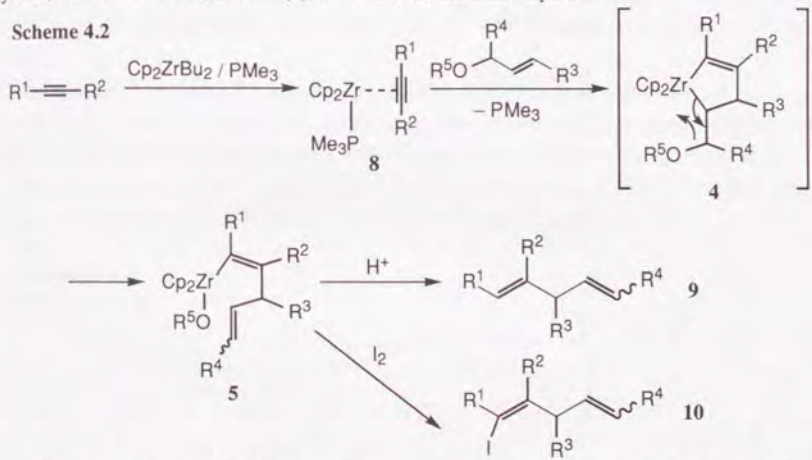
In this chapter I would like to show a novel method to provide vinylzirconation products of unactivated alkynes by a combination of Cp_2ZrEt_2 and vinyl ethers. Vinylzirconation products produced by this method were not reactive toward second alkynes.

Results and Discussion

Allylation of alkynes via zirconocene-alkyne complexes (Method A); Mechanistic consideration

To achieve the allylzirconation reaction of alkynes, the first step should be the coupling of alkynes with allylic ethers on zirconium to form **4** (Scheme 4.2). One accessible way to **4** is the reaction of zirconocene-alkyne complex **8** with an allylic compound. Preparation and reactions of zirconocene-alkyne complexes have already been investigated by several groups.[12] Zirconocene-alkyne complexes have been prepared by the following two methods: (i) adding alkynes and stabilizing reagents such as phosphines[12a,c,f] and DMAP[12g] to Cp_2ZrBu_2 (Negishi reagent); (ii) hydrozirconation of alkynes to produce $Cp_2Zr(CR{=}CHR')Cl$, followed by methylation with MeLi and β-hydrogen abstraction from the alkenyl ligand.[12b,d,e] The former method (i) is more convenient for our purpose. For terminal alkynes, however, method (i) did not give **8** in good yields, therefore the latter method (ii) was useful for terminal alkynes.[13]

Scheme 4.2



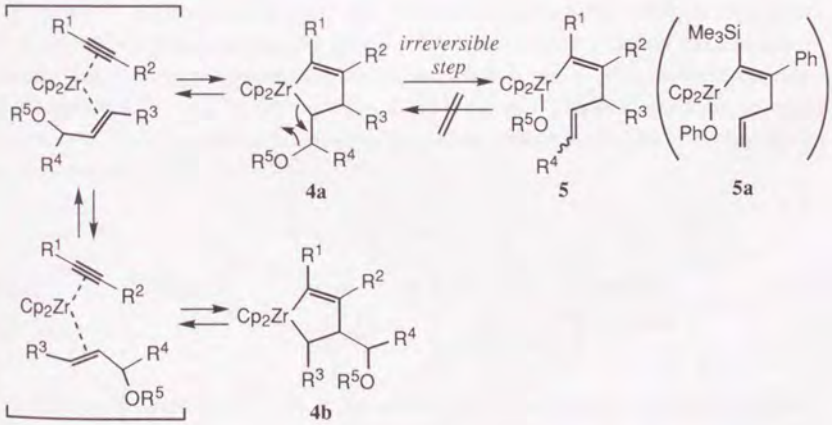
Results are shown in Table 4.1. Alkynes on zirconium reacted with allylic ethers to afford allylated products **9** in good to excellent yields after hydrolysis. Treatment of the reaction mixture with iodine afforded the corresponding alkenyl iodides **10**, showing that the products were alkenylzirconium species. Various allylic ethers can be used for the reaction. Substituted allylic ethers, *trans*-2-hexenyl phenyl ether and 3-benzyloxy-1-octene, also gave allylated products. It is noteworthy that the C-C bond formation occurred exclusively at the γ-position of allylic ethers. Reactions of 1-(trimethylsilyl)alkynes gave the allylated products **9** and **10** with high regioselectivity. Since a trimethylsilyl group stabilizes α-carbanions, α-silyl-alkenylzirconium compounds such as **5** ($R^1 = Me_3Si$) were favored as products as usually observed.[13] This caused the high regioselectivity. The same type of regioselectivity or orientation was also observed in the case of silyl substituted alkynes for other allylmetalation reactions such as allylzincation.[3] 1-Phenylpropyne and 1-octyne, however, gave mixtures of

regioisomers. Addition of Zr and an allyl group to an alkyne was perfectly *syn* in all cases as usually observed.

A plausible mechanism for this allylzirconation of alkynes involves the zirconacyclopentene intermediate **4**. Though the formation of allylzirconocene species in the reaction of Cp_2ZrBu_2 with allylic ethers has been proposed,[14] direct addition of the allylzirconocene to alkynes did not take place under the present conditions. Two isomers, **4a** and **4b**, can be considered as possibilities in the coupling of alkynes with allylic ethers (Scheme 4.3). Even though **4b** might be formed,[15] transformation of **4b** via β-β' C-C bond cleavage in the zirconacyclopentene[16] would afford **4a** under some conditions as observed for allylation of alkenes. Finally, the complex **4a**, in which the -CH(R)OR group occupies the α-position of the zirconacyclopentene, allows β-elimination of an -OR group to give the allylzirconation product **5**. This irreversible β-alkoxy elimination step from **4a** to **5** is totally responsible for inducing the reaction. This mechanism can account for high regioselectivity in C-C bond formation at the γ-position of allylic ethers.

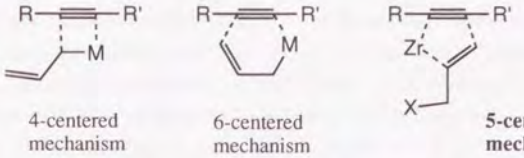
Hydrolysis products of the zirconacyclopentene intermediate **4b** were not observed by gas chromatography in a reasonable amount probably due to the short lifetime of **4b**. The complex **5a** (R^1= Me_3Si, R^2= Ph, R^3= H, R^4= H, R^5= Ph) was formed quantitatively and characterized by NMR spectroscopy. The ^1H NMR spectrum of **5a** showed a singlet peak at 6.03 ppm which was assigned to Cp and the ^{13}C NMR signals were consistent with the structure.

Scheme 4.3



Mechanistic studies of conventional allylmetalations using allylmetals suggested that four-centered and six-centered transition state were plausible.[1] The formation of a mixture of

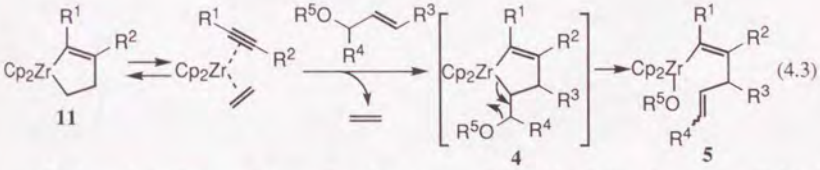
regioisomers is due to these two mechanisms. The mechanism of the present reaction that I am describing here involves the five-membered zirconacyclopentenes for allylzirconation of alkynes and is quite different from those of conventional allylmetalation.[17] This five-centered mechanism is responsible for the high regioselectivity of this allylzirconation reactions.



Allylation of alkynes via zirconacyclopentenes (Method B)

The method for the allylzirconation via the zirconocene-alkyne complex **8** (method A) gave satisfactory results especially for 1-(trimethylsilyl)alkynes or 1-phenylalkynes. This method, however, gave the allylzirconation products in relatively low yields for alkyl substituted alkynes such as 4-octyne. Thus I derived another method using zirconacyclopentene complexes (method B).

Takahashi et al. recently reported a convenient preparative method for zirconacyclopentene **11** and its reactivity.[16b] **11** was prepared quantitatively from Cp_2ZrEt_2 and corresponding alkynes. When **11** was treated with unsaturated compounds such as aldehydes, ketones and alkynes, it showed similar behavior to the zirconocene-alkyne complexes. Cleavage of the β-β' C-C bond in the zirconacycle occurred and the ethylene part was replaced by another unsaturated compound to give a new metalacyclic species. It has been reported that zirconocene-alkyne complex **8** also reacted with aldehydes, ketones and other alkynes to give a new zirconacycle. This reactivity of **11** can be interpreted as it behaving as a "zirconocene-alkyne complex equivalent". Therefore zirconacyclopentene **11** could be used for preparation of **4** using allylic compounds (eq 4.3).[1c]

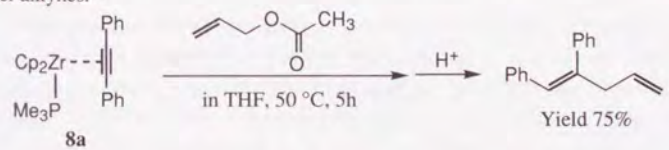


11 showed similar reactivity to **8** and treatment of **11** with allylic ethers gave allylated products as expected. The results are shown in Table 4.2. The reaction using 4-octyne was remarkably improved. The allylation of alkyl substituted alkynes could be improved by this method. Although 1-trimethylsilyl-1-alkynes gave a rather lower yield in contrast to method A, their products also showed high regioselectivity. Deuterolysis of the reaction mixture from 4-

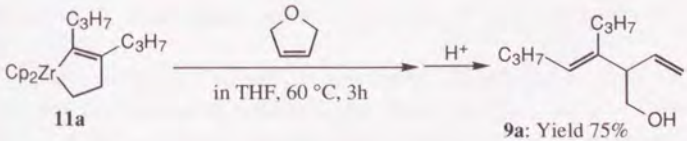
octyne gave the deuterated compound 4-deuterio-3-propyl-1,4-octadiene with 94% D incorporation, showing that the alkenylzirconium species **5** was the product of this reaction. Thus, these two methods A and B can complement each other.

In order to investigate the scope of the reaction, we tried some other allylic compounds. Generally, halogens are good leaving groups and allyl halides are the most typical allylic compounds in this kind of reaction.[18] However, they were not suitable for method A since they interact with trialkylphosphines first. The zirconacyclopentene technique (method B), on the other hand, does not require phosphine ligands. Hence this method has an advantage in allowing allylic halides to participate in the reaction. Results of the allylation with allylic halides are shown in Table 4.3. Allylation products, in fact, were obtained when the zirconacyclopentenes were treated with allylic chlorides. Interestingly, the products obtained from the reactions of 3-chloro-1-butene were selectively *trans*-isomers. It is in sharp contrast with the case of allylic ethers, in which 34:66 to 42:58 mixtures of *trans* and *cis* isomers were obtained. The allylation occurred only at the γ-position of the allylic moiety. Other substituted allylic chlorides such as crotyl chloride and metallyl chloride did not give positive results. Allyl bromide has not given satisfactory results so far. Only a small amount (<10% yield) of the allylation products were obtained and the starting alkyne was liberated in the reaction mixture, in the case of allyl bromide with 5-decyne.

Allyl esters could also be used for the reaction. Treatment of Cp_2Zr(1,2-diphenylacetylene)(PMe_3) **8a** with allyl acetate (method A) gave (*Z*)-1,2-diphenyl-1,4-pentadiene in 75% yield (eq 4.4). Cyclic allylic ethers such as 2,5-dihydrofuran also afforded the desired product **9a** in the reaction with zirconacyclopentene **11a** (R^1=R^2=C_3H_7) (method B, eq 4.5). Buchwald and co-worker have reported a reaction of a zirconocene-cyclooctyne complex, which was prepared from cyclooctenyllithium, with 2,5-dihydrofuran, although there was no report for other alkynes.[19]



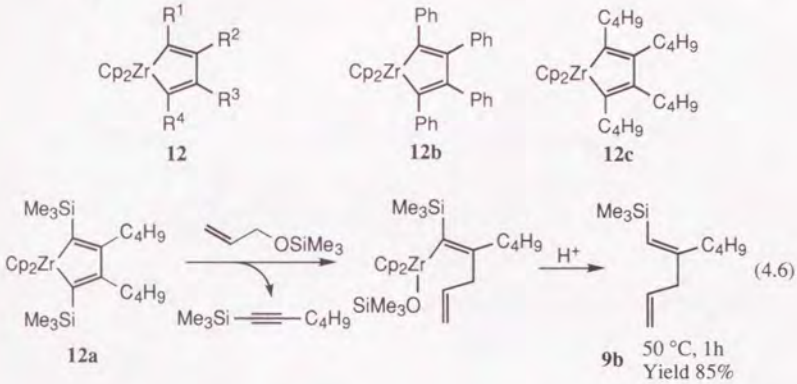
8a Yield 75% (4.4)



11a **9a**: Yield 75% (4.5)

Allylation of alkynes via zirconacyclopentadienes

Zirconacyclopentanes[20] and zirconacyclopent-2-enes[16] showed β-β' C-C bond cleavage in their reactions. In the reactions of zirconacyclopentadiene **12**, however, this type of C-C bond activation has been rarely observed.[13,21] During the course of our investigation, we found that zirconacyclopentadiene **12a** (R^1=R^4=Me_3Si, R^2=R^3=C_4H_9) reacted with allyl trimethylsilyl ether to result in the allylation of the alkyne (eq 4.6). The product (*E*)-2-*n*-butyl-1-(trimethylsilyl)-1,4-pentadiene **9b** was obtained in 85% yield after hydrolysis. This reaction should involve cleavage of the β-β' C-C bond in **12**. This reaction, however, did not occur in other zirconacyclopentadienes such as **12b** and **12c**. This uncommon reactivity of **12a** might be because of instability of the metalacycle due to the bulky α-trimethylsilyl groups.



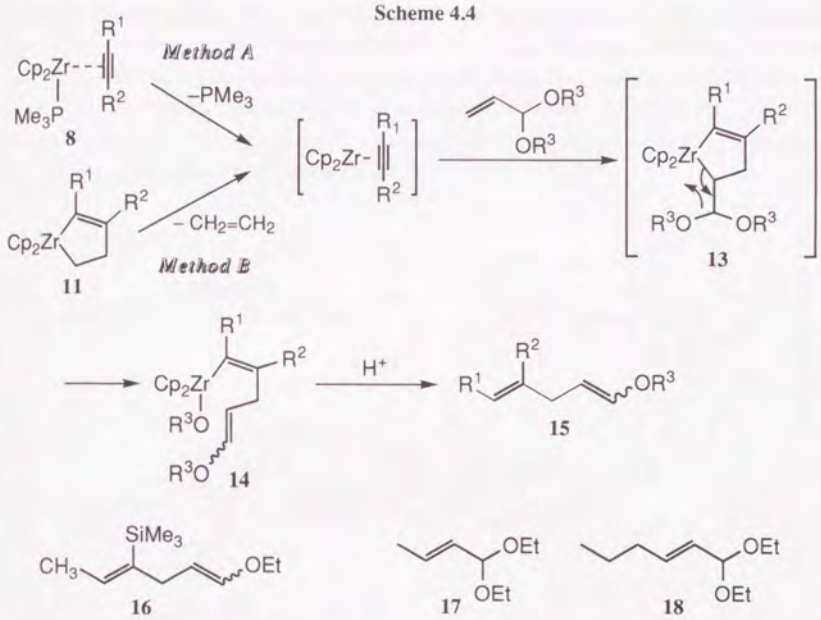
Allylation of alkynes with acetals; formation of vinyl ethers

Introduction of a functional group to the allylation products is also attractive. Although several examples of allylmetalation are known so far, it is relatively difficult to use the functionalized allylmetals. In order to explore this subject in our allylation reactions, we investigated the reaction with α,β-unsaturated acetals. α,β-Unsaturated acetals, which contain an allyl ether moiety, were expected to afford a functionalized allylic moiety in the products **14** (Scheme 4.4). Both methods A and B could be used for the reactions and the results are described in Table 4.4.

Acrolein diethyl acetal was used for the reactions. After hydrolysis of the reaction mixture, vinyl ethers **15** were obtained as the products. Treatment of the products with acid can convert them into aldehydes. The C-C bond formation proceeded exclusively at the terminal carbon of acrolein diethyl acetal in a same way as described above. For 1-trimethylsilyl-2-phenylacetylene and 1-trimethylsilyl-1-octyne, regioselectivity was very high (>98%). In the case of 1-trimethylsilyl-1-propyne, ca. 10% of the regioisomer **16** was observed. The *cis*:*trans* ratio for

the vinyl ether moiety was approximately 1:1. β-Substituted acetals such as **17** and **18** did not give the desired products even at 60 °C.

Scheme 4.4



Carbometalation of alkyne using homoallylic compounds; formation of allylcyclopropanes

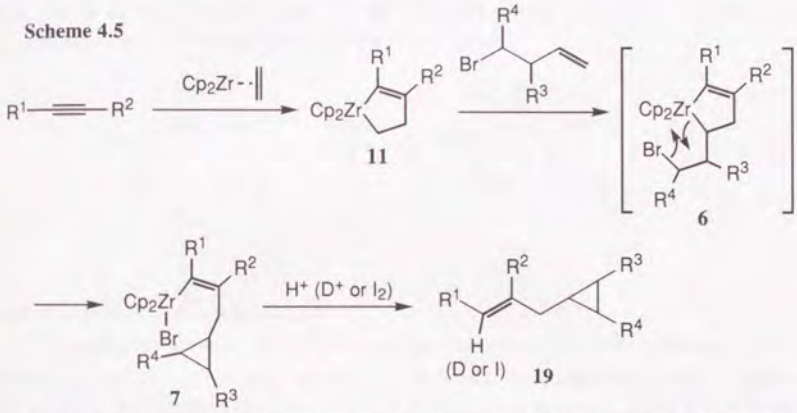
As described above, β-elimination from the α-stem of the zirconacycle was the key step of the allylzirconation of alkynes. This information prompted me to pursue the possibility of γ-elimination from the zirconacyclopentenes. Thus we investigated reactions of alkynes with homoallylic compounds. Homoallylic ethers, however, were not reactive towards the zirconocene-alkyne complexes or zirconacyclopentenes. No γ-elimination products were observed.

Finally we found that treatment of the zirconacyclopentenes with homoallylic bromides gave cyclopropane products **19** after hydrolysis in good yields (Scheme 4.5). Results of the reactions are shown in Table 4.5. Internal alkynes, such as 4-octyne, 3-hexyne, and diphenylacetylene, afforded the corresponding allylcyclopropane derivatives in good yields with high isomeric purity (Run, 1,7,9). Deuterolysis and iodinolysis products revealed the formation of **7** in the reaction mixtures (Run 2, 8, 10). The stereochemistry of the alkenyl moieties was very selective (highly selective *syn* addition) as observed for the allylation reactions of alkynes described above. 1-(Trimethylsilyl)alkynes did not give positive results (Run 13, 14). Similar low reactivity of 1-

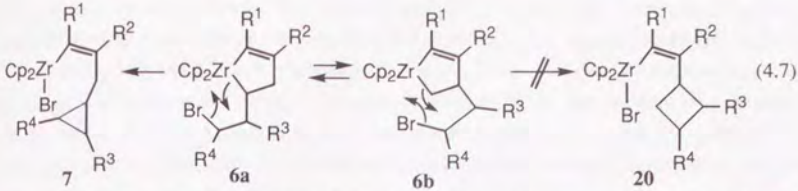
(trimethylsilyl)alkynes was observed in the allylation reactions via zirconacyclopentenes (method B).

Substituted homoallylic bromides were investigated. When a methyl group was at the δ-position in the homoallylic moiety, only an alkyne dimer was obtained in ca. 40 % yield based on zirconium. No desired product was detected (Run 3). An α-substituted homoallylic bromide produced predominantly the *cis*-isomer for the disubstituted cyclopropane moiety (R^1=R^2=C_3H_7, R^3=H, R^4=Me) (Run 5), whereas an β-substituted one gave the *trans*-isomer as a main product (R^1=R^2=C_3H_7, R^3=Et, R^4=H) (Run 6). The stereochemistry of disubstituted cyclopropane derivatives was determined by a known method.[22]

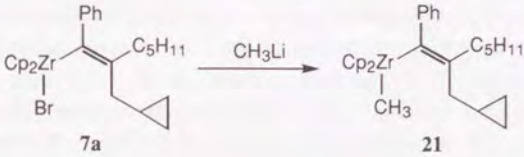
Scheme 4.5



A plausible mechanism for these reactions is as follows. The intermediates **11** reacted with double bond of homoallylic bromides to afford α-substituted zirconacyclopentene compounds **6**. Sequential γ-bromine abstraction by the zirconium metal and attack by the alkyl carbon attached to zirconium produced **7**. Hydrolysis (deuterolysis or iodinolysis) gave the corresponding compounds **19**. Other possible orientations of the double bond in the homoallylic bromides in the reaction with **11** gives β-substituted **6b**. If similar δ-bromine abstraction occurs, cyclobutane derivatives **20** should be formed (eq 4.7). However, the cyclobutane compounds were not detected. This might be because of unstability of cyclobutane structure. Even though **6b** was formed in the reaction, it would be converted into **6a** by isomerization.[23] Recently Whitby et al. showed that the reaction of the zirconocene η^2-imine complex with homoallyl bromide produced cyclopropane compounds.[16] They also suggested that its intermediate was a zirconacycle with the bromoethyl substituent in the α-position. Attempt of the formation of cyclopentane structure via ε-elimination have not succeeded. Not only stability of ring structure would affect the ease of the reaction.



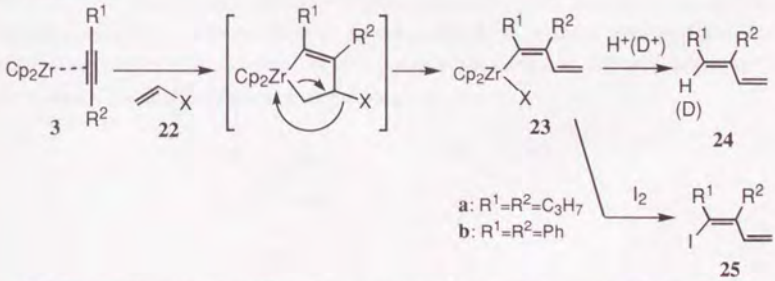
The zirconium containing intermediate species **7a** was investigated by NMR study. The NMR spectra indicated that the complex **7a** was formed in 72% yield. However, the spectra were not clear enough. Therefore the complex **7a** was converted into the methylated compound **21** in 93% yield using MeLi (eq 4.8). The ^{1}H- and ^{13}C-NMR spectra of **21** clearly showed all the protons and carbons which were consistent with the structure.



Vinylzirconation Reaction of Alkynes

The carbozirconation of alkynes shown above involves the elimination reactions from α-substituents of zirconacyclopentene derivatives. This mechanistic consideration led the author to the possibility of elimination from β-substituents of zirconacyclopentenes. In this section I report the novel method to provide vinylzirconation products of unactivated alkynes by a combination of Cp_2ZrEt_2 and vinyl ethers (Scheme 4.6)

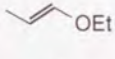
Scheme 4.6



For this reaction zirconacyclopentenes were used as starting compounds (method A; *vide supra*). Vinyl ethers or a vinyl bromide were used as unsaturated compounds. Abstraction of X

group from zirconacyclopentene was expected to afford vinylzirconation products of alkynes. Typical procedure is as follows. To a solution of Cp_2ZrEt_2, which was prepared from Cp_2ZrCl_2 (1.25 mmol, 0.365g) and 2 equiv of EtMgBr (2.5 mmol, 2.5 mL, 1.0 M THF solution) in 3.5 ml of THF at -78°C, was added 4-octyne (1 mmol, 0.110g) at -78°C. The mixture was warmed to 0°C and stirred for 2h. A clean formation of zirconacyclopentene was observed (90% yield by NMR) as described previously.[16b] To this was added 1.5 mmol of vinyl ethyl ether (0.108 g) at room temperature. After stirring the mixture for 6 h at 50°C, quenching with I_2 gave *cis*-4-iodo-3-propyl-1,3-heptadiene **25a** ($R^1 = R^2 = C_3H_7$) in 90% yield.

Results are shown in Table 4.6. In the case of symmetrical internal alkynes such as 4-octyne and diphenylacetylene vinylzirconation products were obtained in high yields. After hydrolysis the desired product **24** was obtained in 88% yield (R^1=R^2=C_3H_7) with a high isomeric purity (>98%). This reaction proceeded in a syn fashion (>98%) as usually observed for carbometalation of alkynes. Vinyl butyl ether or vinyl bromide could be used for this reaction. When vinyl bromide was used, the reaction completed after 1h at room temperature. However, the yield was relatively low (66 %). Substituted alkenyl ethers such as **26** and **27** did not give the corresponding products. Five membered cyclic vinyl ether 1,2-dihydrofuran **28** reacted smoothly to give **29** in 66 % yield ($R^1 = R^2 = C_3H_7$, cis:trans = 61:39) after hydrolysis.



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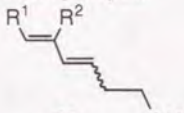

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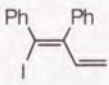
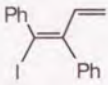
The vinylzirconation product **23b** ($R^1 = R^2$ = Ph) was clearly observed by ^1H and ^{13}C NMR spectroscopy and those spectrum were consistent with the formula. Deuterolysis of the reaction mixture ($R^1 = R^2$ = Ph, X = OEt) gave *cis*-1,2-diphenyl-1-deuterio-1,3-butadiene in 78% yield with >98 % deuterium incorporation. Iodination of the reaction mixture, however, gave a 1:1 mixture of **25b** and **30** in 78% combined yield. Stereoisomerization occurred during the iodination. In the case of alkyl substituted alkynes such as 4-octyne, no stereoisomerization was observed during the iodination reaction. Zirconocene-alkyne complex stabilized with PMe_3, Cp_2Zr(1,2-diphenylacetylene)(PMe_3) did not react with vinyl ethers at 50°C even after 24h. This is in contrast to the allylzirconation of alkynes using allylic ethers.



25b



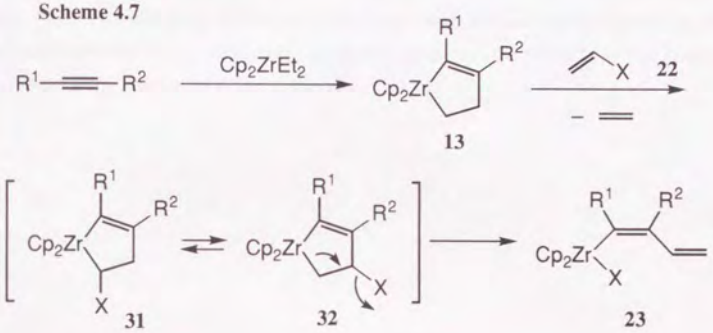
30

Unsymmetric alkynes such as 1-phenyl-1-propyne and 1-phenyl-1-hexyne gave a mixture of regioisomers. For terminal alkynes, this method gave a low yield of the product. Zirconocene-1-

octyne complex prepared from $Cp_2Zr(H)Cl$[12d] reacted with vinyl ether to afford vinylzirconation product with high regioselectivity (99 %).

The plausible reaction mechanism of this reaction is shown in scheme 4.7. It is known that the reaction of alkynes with Cp_2ZrEt_2 gives zirconacyclopentene compounds. And also ethylene part of the zirconacyclopentene can be replaced by unsaturated compounds. Although the intermediate compound could not be detected, alkoxy or bromo-substituted zirconacyclopentenes are the reasonable intermediate compounds. Two regioisomers, **31** and **32**, could be considered in equilibrium. Abstraction of X group from β-position of zirconacyclopentene **32** gives the desired vinylzirconation products of alkynes. Actually a reaction of zirconacyclopentene **11** ($R^1 = R^2 = Ph$) with ethyl vinyl ether gave **23b** ($R^1 = R^2 = Ph$) in 83 % yield (yield was determined by ^1H NMR). Its hydrolysis product **24b** ($R^1 = R^2 = Ph$) was obtained in 85 % yield.

Scheme 4.7



Conclusion

In conclusion, the current work represents novel carbozirconation reactions of alkynes. These reactions are summarized by the following points. (i) Zirconocene-alkyne complexes reacted with allylic compounds to afford the allylzirconation products. (ii) Zirconacyclopentenes, which are prepared from alkynes and Cp_2ZrEt_2, also gave the allylzirconation products when treated with allylic compounds. (iii) Zirconacyclopentadiene with α-trimethylsilyl groups also showed similar reactivity toward allylic ethers. The allylation proceed via β-β' C-C bond cleavage in the reactions of the zirconacyclopentenes and the zirconacyclopentadienes. (iv) The allylation reaction proceeds via a five-membered ring intermediate and subsequent β-elimination. High γ-selectivity of the C-C bond formation in the allylation is explained by this mechanism. This mechanism is uncommon compared with conventional allylmetalation mechanisms. (v) An α,β-unsaturated acetal was used for the allylation reactions to give vinyl ether derivatives as the products. (vi) The reactions of homoallyl bromides with the zirconacyclopentenes afforded allylcyclopropane derivatives as the carbozirconation products. (vii) Vinylzirconation of alkynes were achieved using vinyl ether or vinyl bromide.

Table 4.1. Allylzirconation Reactions of Alkynes by the Reactions of Zirconocene Alkyne Complexes with Allylic Ethers; *Formation of Hydrolysis Products*[a]

Run	Alkyne	Allylic ether	Temp /°C	Time /h	Hydrolysis product **9**	Yield /%	Isomeric purity/%
1	$Me_3Si-\equiv-C_6H_{13}$	OPh	35	3	Me_3Si, C_6H_{13}	81	97
2	$Me_3Si-\equiv-C_6H_{13}$	OEt	35	6	Me_3Si, C_6H_{13}	80	95
3	$Me_3Si-\equiv-C_6H_{13}$	O	35	3	Me_3Si, C_6H_{13}	94	>99
4	$Me_3Si-\equiv-C_6H_{13}$	C_3H_7, OPh	50	48	Me_3Si, C_6H_{13}, C_3H_7	72	>99
5	$Me_3Si-\equiv-C_6H_{13}$	C_5H_{11}, OBn	35	24	Me_3Si, C_6H_{13}, C_5H_{11}	80	b
6	$Me_3Si-\equiv-Ph$	OPh	35	3	Me_3Si, Ph	97	98
7	$Ph-\equiv-Ph$	OPh	35	24	Ph, Ph	97	>99
8	$C_3H_7-\equiv-C_3H_7$	OPh	35	1	C_3H_7, C_3H_7	67	>99
9	$Ph-\equiv-CH_3$	OPh	35	24	Ph, CH_3	76	62
10[c]	$C_6H_{13}-\equiv$	O	35	24	C_6H_{13}	73	d

a) Yields were determined by GC. Unless otherwise mentioned, the alkyne complex was prepared by the method (i) with PMe_3. b) cis:trans = 58:42. c) Zirconocene(1-octyne)(PMe_3) was prepared by method (ii).[12d]
d) 2-hexyl-1,4-pentadiene:(E)-1,4-undecadiene = 78:22.

Table 4.1 (continued).

Allylzirconation Reactions of Alkynes by the Reactions of Zirconocene-alkyne Complexes with Allylic Ethers; *Formation of Alkenyl Iodides*[a]

Run	Alkyne	Allylic ether	Temp /°C	Time /h	Iodinolysis product **10**	Yield /%	Isomeric purity/%
1	$Me_3Si-\equiv-C_6H_{13}$	OPh	35	3	Me_3Si, C_6H_{13}, I	84	99
2	$Me_3Si-\equiv-C_6H_{13}$	OEt	35	6	Me_3Si, C_6H_{13}, I	72	96
3	$Me_3Si-\equiv-C_6H_{13}$	O	35	3	Me_3Si, C_6H_{13}, I	88	>99
4	$Me_3Si-\equiv-C_6H_{13}$	C_3H_7, OPh	50	48	Me_3Si, C_6H_{13}, I, C_3H_7	75	>99
5	$Me_3Si-\equiv-Ph$	OPh	35	3	Me_3Si, Ph, I	94	98
6	$Ph-\equiv-Ph$	OPh	35	24	Ph, Ph, I	87	>99
7	$C_3H_7-\equiv-C_3H_7$	OPh	35	1	C_3H_7, C_3H_7, I	71	>99
8	$Ph-\equiv-CH_3$	OPh	35	24	Ph, CH_3, I	76	60
9[b]	$C_6H_{13}-\equiv$	O	35	24	C_6H_{13}, I	56	c

a) Yields were determined by GC. Unless otherwise mentioned, the alkyne complex was prepared by the method (i) with PMe_3. b) Zirconocene(1-octyne)(PMe_3) was prepared by method (ii)[12d].

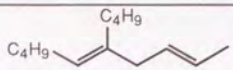
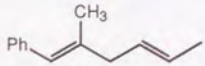
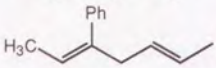
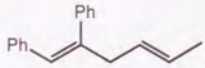
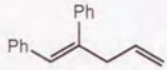
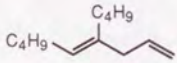
c) 1-iodo-2-hexyl-1,4-pentadiene:(Z)-5-iodo-1,4-undecadiene = 81:19.

Table 4.2 Allylzirconation Reactions of Alkynes via Zirconacyclopentenes[a]

Alkyne	Allylic ether	Temp /°C	Time /h	Hydrolysis Product **9**	Yield /%	Isomeric purity/%
C_3H_7—≡—C_3H_7	OPh	50	3	C_3H_7, C_3H_7	91	-
C_3H_7—≡—C_3H_7	O	35	1	C_3H_7, C_3H_7	99	-
C_4H_9—≡—C_4H_9	$OSiMe_3$	50	1	C_4H_9, C_4H_9	97	-
C_3H_7—≡—C_3H_7	C_5H_{11}, OBn	50	24	C_3H_7, C_3H_7, C_5H_{11}	60	cis/tr = 66:34
Ph—≡—Ph	OPh	r.t.	3	Ph, Ph	89	>99
Ph—≡—CH_3	O	35	3	CH_3, Ph	91[b]	regiosel. = 65%
Me_3Si—≡—C_6H_{13}	OPh	35	24	C_6H_{13}, Me_3Si	68	96
Me_3Si—≡—Ph	OPh	35	3	Ph, Me_3Si	56	98

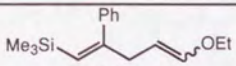
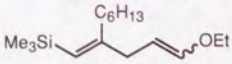
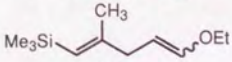
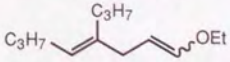
a) Yields were determined by GC. b) Combined yield of regioisomers

Table 4.3 Allylzirconation of Alkynes using Allylic Chlorides via Zirconacyclopentenes[a]

Alkyne	Allylic chloride	Temp /°C	Time /h	Product **9**	Yield /%	Stereosel. /%
C_4H_9—≡—C_4H_9		50	3		53	91
Ph—≡—CH_3		50	6		46	91
					32	97
Ph—≡—Ph		50	1		79	>99
Me_3Si—≡—C_4H_9				N.R.	-	-
Ph—≡—Ph		r.t.	1		95	-
C_4H_9—≡—C_4H_9		r.t.	1		69	-

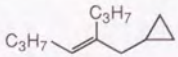
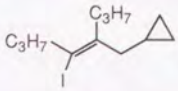
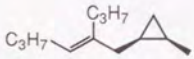
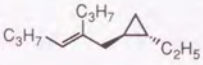
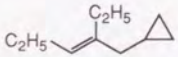
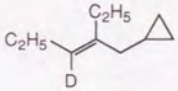
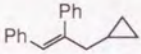
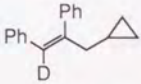
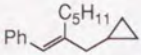
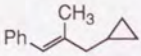
a) Yields were determined by GC.

Table 4.4 Reactions of Alkynes with Acetals Mediated by Zirconium; *Formation of Vinyl Ethers*[a]

Alkyne	Method[b]	Temp /°C	Time /h	Hydrolysis product **15**	Yield /%	Regiosel for alkyne/%	cis:trans for vinyl ether
Me_3Si—≡—Ph	A	35	1		71	>98	53:47
Me_3Si—≡—C_6H_{13}	A	35	1		75	>98	48:52
Me_3Si—≡—CH_3	A	35	1		81[c]	89	41:59
C_3H_7—≡—C_3H_7	B	r.t.	48		61	-	49:51

a) Yields were determined by GC.
b) Method A: via zirconocene-alkyne complexes, Method B: via zirconacyclopentenes.
c) Combined yield of regioisomers

Table 4.5 Reactions of Alkynes with Homoallylic Bromides; *Formation of Cyclopropanes*

Run	Alkyne	Homoallylic halide	Temp /°C	Time /h		Main product **19**	Yield[a] /%	Isomeric purity/%
1	C_3H_7—≡—C_3H_7	Br	r.t.	24	H^+		68	>99
2	C_3H_7—≡—C_3H_7	Br	r.t.	24	I_2		50	>99
3	C_3H_7—≡—C_3H_7	Br	65	24	H^+	b	0	-
4	C_3H_7—≡—C_3H_7	OPh	50	12	H^+	N.R.[c]	0	-
5	C_3H_7—≡—C_3H_7	Br	50	24	H^+		64	74[d,e]
6	C_3H_7—≡—C_3H_7	Br, Et	40	24	H^+		59	74[d,f]
7	C_2H_5—≡—C_2H_5	Br	r.t.	24	H^+		70	>98
8	C_2H_5—≡—C_2H_5	Br	r.t.	24	D^+		70	(95)[g]
9	Ph—≡—Ph	Br	r.t.	12	H^+		80	>98
10	Ph—≡—Ph	Br	r.t.	24	D^+		71	(94)[g]
11	Ph—≡—C_5H_{11}	Br	40	24	H^+		68	>98
12	Ph—≡—Me	Br	r.t.	24	H^+		85	85[h]
13	Me_3Si—≡—$SiMe_3$	Br	50	24	H^+	N.R.[c]	0	-
14	Me_3Si—≡—Me	Br	40	12	H^+	b	0	-
15[i]	C_6H_{13}—≡	Br	r.t.	12	H^+		59	77[j]

a) Yields were determined by GC. Combined yields of isomers. b) Alkyne dimer was formed. c) No desired products. d) A mixture of stereoisomers of cyclopropane moiety. e) Cis:trans = 74:26. f) Cis:trans = 26:74. g) Deuterium incorporation. h) Two regioisomers for Me and Ph groups of phenylpropyne were obtained in a ratio of 85:15. i) This reaction was carried out using zirconocene-alkyne complex without PMe_3 prepared by method (ii).[12d] j) Two regioisomers for C_6H_{13} group of 1-octyne were obtained in a ratio of 77:23.

Table 4.6 Vinylzirconation Reactions of Alkynes using Cp_2ZrEt_2 and Vinyl Ethers

Run	Alkyne	Vinyl Ether	Temp /°C	Time /hr		Product	Yield[a] /%
1	C_3H_7—≡—C_3H_7	OEt	50	6	H^+	C_3H_7 C_3H_7	88
2	C_3H_7—≡—C_3H_7	OBu	50	6	H^+	C_3H_7 C_3H_7	81
3	C_3H_7—≡—C_3H_7	OEt	50	6	I_2	C_3H_7 C_3H_7 I	90
4	C_6H_5—≡—C_6H_5	OEt	50	3	H^+	C_6H_5 C_6H_5	85
5	C_6H_5—≡—C_6H_5	OEt	50	3	D^+	C_6H_5 C_6H_5 D	78
6	C_6H_5—≡—C_6H_5	OEt	50	3	I_2	C_6H_5 C_6H_5 I	78[b]
7	C_6H_5—≡—C_5H_{11}	OBu	50	24	H^+	C_6H_5 C_5H_{11}	70[c]
8	C_6H_5—≡—CH_3	OEt	50	12	H^+	C_6H_5 CH_3	66[d]
9	C_6H_{13}—≡	OEt	35	12	I_2	C_6H_{13} I	57[e]

a)Yields were determined by GC. Combined yields of isomers. b) A 50:50 mixture of E/Z isomers. c) A mixture of 70:30 regioisomers for C_6H_5 and C_5H_{11} groups. d)A mixture of 81:19 regioisomers for C_6H_5 and CH_3 groups. e) This reaction was carried out using zirconocene-alkyne complex without PMe_3 prepared from $Cp_2Zr(H)Cl$ as in the literature.[12d]

Experimental Section

General. All reactions involving organozirconium compounds were carried out under a nitrogen atmosphere. Teterahydrofuran was dried over sodium/benzophenone and then distilled. Zirconocene dichloride was purchased from Aldrich Chemical Company, Inc. Ethylmagnesium bromide (THF solution) and butyllithium (hexane solution) were purchased from Kanto Chemicals Co. Ltd. Other organic chemicals were purchased from Tokyo Chemical Industry Co., Ltd. or Wako Pure Chemical Ind., Ltd. Some alkynes were prepared by known methods. ^{1}H (270 MHz) and ^{13}C (67.5 MHz) NMR spectra were recorded on a JEOL EX270 NMR spectrometer, infrared spectra on a Shimadzu FTIR-4200, GC-MS on a Shimadzu GCMS-QP1000EX and high resolution mass spectroscopy on a Shimadzu-Kratos CONCEPT IS. Deuterium incorporation was determined by ^{13}C NMR spectra (gated decoupling pulse technique without NOE).

Allylation of alkynes via zirconocene-alkyne complexes (method A)

Representative Procedure; (Z)-2-phenyl-1-trimethylsilyl-1,4-pentadiene. Typical procedure for the allylation of alkynes via the zirconocene-alkyne complex is as follows. To Cp_2ZrBu_2 prepared from Cp_2ZrCl_2 (365 mg, 1.25 mmol) and 2 equiv of *n*-BuLi (1.6 M hexane solution, 2.5 mmol) in 5 mL of THF was added 1.5 mmol of PMe_3 (1.25 mL of 1.0M solution in THF) at -78°C. The mixture was warmed up to room temperature and stirred for 1 h. To this mixture was added 1-phenyl-2-(trimethylsilyl)acetylene (174 mg, 1.0 mmol) at room temperature. Zirconocene alkyne complex **8** was cleanly formed after 1h. After addition of allyl phenyl ether (268 mg, 2.0 mmol), the mixture was stirred for 3h at 35 °C. The reaction mixture was quenched with 3.0 N HCl, extracted with Et_2O, washed with saturated aqueous $NaHCO_3$ and brine and then dried over $MgSO_4$. Purification by flash column chromatography (hexane) gave the title compound (97% yield based on alkyne with 98% regioselectivity). The yield was determined by GC. The product was characterized by ^{1}H and ^{13}C NMR and high resolution mass spectroscopy. ^{1}H NMR ($CDCl_3$, Me_4Si): δ -0.19 (s, 9H), 3.34 (dq, J = 7, 1 Hz, 2H), 4.99-5.06 (m, 2H), 5.59 (t, J = 1 Hz, 1H), 5.75-5.91 (m, 1H), 7.13-7.17 (m, 2H), 7.24-7.32 (m, 3H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 0.66, 47.36, 117.08, 127.61, 128.38, 128.58, 136.54, 144.66, 158.05. High resolution mass spectroscopy, calcd for $C_{14}H_{20}Si$: 216.1334, found: 216.1326.

(*E*)-2-*n*-Hexyl-1-trimethylsilyl-1,4-pentadiene. The title compound was prepared in a similar manner to that described above, using 1-(trimethylsilyl)-1-octyne (0.182 g, 1.0 mmol) instead of 1-phenyl-2-(trimethylsilyl)-acetylene. Yield 81% (by GC) with 97% regioselectivity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.09 (s, 9H), 0.89 (t, J = 7 Hz, 3H), 1.29-1.40 (m, 8H), 2.08-2.14 (dd, J = 7, 8 Hz, 2H), 2.80-2.83 (dd, J = 7, 1 Hz, 2H), 4.99-5.05 (m, 2H), 5.20 (dd, J = 1, 1 Hz, 1H), 5.73-5.88 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 0.38, 14.07, 22.62, 29.02, 29.60,

31.81, 36.24, 43.45, 115.95, 124.24, 136.89, 158.00. High resolution mass spectroscopy, calcd for $C_{14}H_{28}Si$: 224.1960, found: 224.1951.

(1*E*)-2-*n*-Hexyl-1-(trimethylsilyl)-1,4-decadiene. The title compound was obtained as a mixture of two isomers, (1*E*,4*Z*)/(1*E*,4*E*)=58/42. 80% combined yield (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ -0.08 (s, *E-isomer*), 0.00 (s, *Z*), 0.78-0.83 (m, CH_3 x 4), 1.16-1.35 (m), 1.90-2.05 (m), 2.66 (d, *J* = 5 Hz, 2H, *E-isomer*), 2.72 (d, *J* = 6.9 Hz, *Z-isomer*), 5.10-5.12 (m), 5.23-5.44 (m). ^{13}C NMR ($CDCl_3$, Me_4Si): δ (1*E*,4*Z*-isomer) 0.41, 14.09, 14.09, 22.62, 22.66, 27.19, 29.06, 29.24, 29.38, 31.59, 31.86, 36.41, 36.80, 123.45, 127.40, 131.35, 158.58; (1*E*,4*E*-isomer) 0.41, 14.09, 14.09, 22.57, 22.66, 29.24, 29.67, 29.67, 31.39, 31.86, 32.56, 36.19, 42.39, 123.59, 128.08, 132.40, 159.08. High resolution mass spectroscopy; calcd for $C_{19}H_{38}Si$: 294.2743, found: 294.2753.

(*Z*)-1,2-Diphenyl-1,4-pentadiene. Yield 97% with >99% stereoselectivity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 3.22 (dd, *J* = 7, 1 Hz, 2H), 5.04-5.14 (m, 2H), 5.81-5.96 (m, 1H), 6.45 (s, 1H), 6.91-7.54 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 45.35, 117.30, 126.91, 127.61, 127.70, 128.49, 129.12, 129.23, 129.69, 136.52, 137.98, 141.84, 141.88.

(*E*)-4-Allyl-4-octene. 67% yield by method A (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.887 (t, 3H, *J* = 7 Hz), 0.894 (t, 3H, *J* = 7 Hz), 1.37 (tq, 2H, *J* = 7, 7 Hz), 1.40 (tq, 2H, *J* = 7, 7 Hz), 1.99 (dt, 2H, *J* = 7, 7 Hz), 2.00 (t, 2H, *J* = 7 Hz), 2.74-2.69 (m, 2H), 4.99 (ddt, 1H, $|^2J|$ = 2 Hz, ^3J = 10 Hz, $|^4J|$ = 1.2 Hz), 5.02 (ddt, 1H, $|^2J|$ = 2 Hz, ^3J = 17 Hz, $|^4J|$ = 1.5 Hz), 5.16 (t, 1H, *J* = 7 Hz), 5.78 (ddt, 1H, *J* = 10, 17, 7 Hz). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.93, 14.14, 21.47, 23.23, 29.99, 32.22, 41.60, 115.36, 126.25, 137.63, 137.68. MS (EI) *m/e* 152 (M^+). High resolution mass spectroscopy; calcd for $C_{11}H_{20}$: 152.1565, found: 152.1565.

(*E*)-1-Phenyl-2-methyl-1,4-pentadiene/(*Z*)-4-phenyl-1,4-hexadiene. Obtained as a 62/38 mixture of two regioisomers, in 67% combined yield (by GC). *1-Phenyl-2-methyl-1,4-pentadiene.* ^{1}H NMR ($CDCl_3$, Me_4Si): δ 1.85 (d, *J* = 1 Hz, 3H), 2.90 (d, *J* = 7 Hz, 2H), 5.06-5.15 (m, 2H), 5.72-5.96 (m, 1H), 6.30 (s, 1H), 7.15-7.35 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 17.83, 44.96, 116.33, 125.96, 126.43, 128.01, 128.80, 136.40, 137.27, 139.73. *2-phenyl-1-methyl-1,4-pentadiene.* ^{1}H NMR ($CDCl_3$, Me_4Si): δ 1.58-1.61 (dq, *J* = 7, 1 Hz, 3H), 3.06-3.09 (dq, *J* = 7, 1 Hz, 2H), 4.95-5.04 (m, 2H), 5.56 (dt, *J* = 7 Hz, 1H), 5.72-5.96 (m, 1H), 7.15-7.35 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.75, 43.34, 115.78, 122.23, 125.73, 127.98, 128.50, 136.66, 138.42, 140.09. High resolution mass spectroscopy; calcd for $C_{12}H_{14}$: 158.1096, found: 158.1098.

(*E*)-1,4-Undecadiene/2-*n*-hexyl-1,4-pentadiene. Obtained as a 78/22 mixture of two regioisomers, in 73% combined yield (by GC). *(E)-1,4-Undecadiene.* ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, *J* = 6.6 Hz, 3H, 11), 1.20-1.45 (m, 8H), 1.99 (dt, *J* = 6.6, 6.6 Hz, 2H, 6), 2.73 (dd, *J* = 6, 6 Hz, 2H, 3), 4.94-5.08 (m, 2H, 1), 5.34-5.51 (m, 2H, 2,4), 5.74-5.90 (m, 1H, 5). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.11, 22.66, 28.88, 29.49, 31.77, 32.61, 36.78, 114.70, 127.49, 131.86, 137.54. *2-n-Hexyl-1,4-pentadiene.* ^{13}C NMR ($CDCl_3$, Me_4Si): δ

14.11, 22.66, 27.62, 29.07, 31.77, 36.01, 40.79, 109.70, 115.92, 136.62, 148.52. High resolution mass spectroscopy; calcd for $C_{11}H_{20}$: 152.1565, found: 152.1565.

Allylation of alkynes via zirconocene-alkyne complexes (method A); iodination products. Representative procedure; (*E*)-1-iodo-2-phenyl-1-(trimethylsilyl)-1,4-pentadiene. The allylzirconation reaction was carried out by the same method as detailed above. Typical procedure for iodinolysis of the allylzirconation products is as follows. To the reaction mixture was added slightly excess of iodine in THF solution at 0 °C. After stirring at room temperature overnight, the reaction mixture was quenched with 3.0 N HCl and the usual workup gave the title compound (97% yield based on alkyne with 98% regioselectivity). Yield was determined by GC. ^{1}H NMR ($CDCl_3$, Me_4Si): δ -0.12 (s, 9H), 3.46-3.49 (dd, *J* = 7, 1 Hz, 2H), 5.01-5.08 (m, 2H), 5.64-5.79 (m, 1H), 7.03-7.10 (m, 2H), 7.24-7.31 (m, 3H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 0.85, 52.28, 112.52, 117.03, 127.94, 128.41, 132.79, 141.88, 157.34. High resolution mass spectroscopy, calcd for $C_{14}H_{19}ISi$: 342.0301, found: 342.0302.

(*E*)-2-*n*-Hexyl-1-iodo-1-(trimethylsilyl)-1,4-pentadiene. 72-88% yield (by GC) with 96-99% isomeric purity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.29 (s, 9H), 0.89 (t, *J* = 7 Hz, 3H), 1.18-1.43 (m, 8H), 2.25-2.28 (dd, *J* = 6, 3 Hz, 2H), 3.18-3.22 (ddd, *J* =7, 2, 1 Hz, 2H), 5.06-5.16 (m, 2H), 5.71-5.86 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 2.10, 14.05, 22.59, 29.31, 29.40, 31.66, 35.54, 49.02, 108.98, 116.33, 134.19, 157.18. High resolution mass spectroscopy, calcd for $C_{14}H_{27}ISi$: 350.0927, found: 350.0934.

(*Z*)-2-*n*-Hexyl-1-iodo-3-n-propyl-1-(trimethylsilyl)-1,4-pentadiene. 75% yield (by GC) with >99% isomerical purity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.30 (s, 9H), 0.86-0.95 (m, 6H), 1.16-1.43 (m, 12H), 2.29 (t, *J* = 7.2 Hz, 2H), 3.80 (m, 1H), 4.76-5.15 (m, 2H), 5.70-5.83 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 2.13, 14.09, 14.27, 20.18, 22.59, 29.30, 29.44, 31.80, 33.64, 35.51, 58.85, 107.90, 115.29, 137.88, 156.27. High resolution mass spectroscopy; calcd for $C_{17}H_{33}ISi$: 392.1398, found: 392.1386.

(*E*)-1,2-Diphenyl-1-iodo-1,4-pentadiene. 87% yield by GC. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 3.58 (d, *J* = 6.6 Hz, 2H), 5.07-5.22 (m, 2H), 5.75-5.90 (m, 1H), 6.95-7.11 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 49.27, 101.27, 116.78, 126.66, 127.58, 127.74, 128.30, 128.98, 129.81, 131.57, 133.44, 139.76, 146.11. High resolution mass spectroscopy; calcd for $C_{17}H_{15}I$: 346.0220, found: 346.0234.

(*Z*)-5-Iodo-4-*n*-propyl-1,4-octadiene. 71% yield by the method A (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.87-0.94 (m, 6H), 1.35-1.48 (m, 2H), 1.49-1.63 (m, 2H), 2.15 (t, *J* = 7.9 Hz, 2H), 2.51 (t, *J* = 7.4 Hz, 2H), 3.02 (d, *J* = 6.6 Hz, 2H), 5.03-5.13 (m, 2H), 5.67-5.82 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 12.94, 14.02, 21.83, 23.09, 33.67, 43.04, 46.99, 106.38, 113.90, 134.73, 141.67. High resolution mass spectroscopy; calcd for $C_{11}H_{19}I$: 278.0533, found: 278.0540.

(*Z*)-1-Iodo-2-methyl-1-phenyl-1,4-pentadiene/(*E*)-5-iodo-4-phenyl-1,4-hexadiene. Obtained as a 60:40 mixture of two isomers. 76% combined yield (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 1.69 (s), 2.39 (s), 3.18 (d, *J*=5.9 Hz), 3.33 (dt, *J*=6.6, 1.5 Hz), 4.98-5.24 (m, 2H), 5.63-5.90 (m, 1H), 7.07-7.33 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 19.08, 31.82, 48.45, 49.04, 95.87, 99.24, 116.44, 116.53, 126.97, 127.37, 128.08, 128.19, 128.19, 128.77, 133.62, 133.92, 139.53, 140.84, 143.61, 144.62. High resolution mass spectroscopy; calcd for $C_{12}H_{13}I$: 284.0062, found: 284.0051.

(*Z*)-5-Iodo-1,4-undecadiene/2-*n*-hexyl-1-iodo-1,4-pentadiene. Obtained as a 81/19 mixture of two regioisomers, in 73% combined yield (by GC). *(Z)-5-Iodo-1,4-undecadiene.* ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.89 (t, *J* = 6.6 Hz, 3H), 1.25-1.35 (m, 6H), 1.52 (tt, *J* = 7.1 Hz, 2H), 1.99 (dt, *J* = 6.6, 6.6 Hz, 2H), 2.48 (td, ^3J = 7.3 Hz, ^4J = 0.8 Hz, 2H), 2.88 (dd, *J* = 6.4, 6.4 Hz, 2H), 5.00-5.13 (m, 2H), 5.51 (tt, ^3J = 6.9 Hz, ^4J = 1.2 Hz, 1H), 5.65-5.87 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.07, 22.59, 27.87, 29.33, 31.57, 40.70, 45.21, 111.18, 115.52, 131.73, 134.86. *2-n-Hexyl-5-iodo-1,4-pentadiene.* ^{1}H NMR ($CDCl_3$, Me_4Si): δ 2.18 (td, ^3J = 7.5 Hz, ^4J = 1 Hz, 2H), 2.97 (ddd, ^3J = 6.6, ^4J = 1.5, 1.5 Hz, 2H), 5.94 (t, ^4J = 1.3 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.07, 22.59, 27.62, 28.82, 31.57, 37.20, 41.81, 75.43, 116.57, 133.91, 149.52. High resolution mass spectroscopy; calcd for $C_{11}H_{19}I$: 278.0532, found: 278.0529.

Reaction of Cp_2Zr(1-phenyl-2-(trimethylsilyl)acetylene)(PMe_3) with ally phenyl ether; preparation of 5a. To a solution of Cp_2ZrCl_2 (1.461 g, 5.0 mmol) in THF (20 mL) was added dropwise *n*-BuLi (1.6 M in *n*-hexane, 6.25 mL, 10.0 mmol) at -78 °C and stirred for 1h. After addition of trimethylphosphine (1.0 M in THF, 5.5 mmol) at -78 °C, the reaction mixture was gradually warmed up to room temperature and stirred for 1h, and then 1-phenyl-2-(trimethylsilyl)acetylene (0.872 g, 5.0 mmol) was added. After stirring for 3h at room temperature, allyl phenyl ether (0.670 mg, 5.0 mmol) was added and the mixture was stirred at 35 °C overnight. The solvent was then removed *in vacuo* and the residue was washed with hexane and extracted with C_6D_6. ^{1}H- and ^{13}C NMR observation indicated the quantitative formation of **5a**. ^{1}H NMR (Me_4Si, C_6D_6): δ 0.02 (s, 9H), 2.76 (ddd, *J*=6.3, 1.6, 1.3 Hz, 2H), 4.87-4.96 (m, 2H), 5.69-5.84 (m, 1H), 6.03 (s, 10H), 6.59-6.64 (m, 2H), 6.85-6.91 (m, 1H), 7.04-7.26 (m, 7H). ^{13}C NMR (Me_4Si, C_6D_6): δ 3.94, 50.89, 112.00, 115.94, 118.47, 119.87, 126.25, 127.89, 129.00, 129.72, 136.96, 148.70, 158.29, 164.78, 185.21.

Allylation of alkynes via zirconacyclopentenes (method B); Representative procedure; (*E*)-4-allyl-4-octene. Typical procedure for the allylation reactions of alkynes via zirconacyclopentenes is as follows. To a solution of Cp_2ZrCl_2 (365 mg, 1.25 mmol) in THF (5 mL) was added ethylmagnesium bromide (0.93 M THF solution; 2.5 mmol) at -78 °C and was stirred for 1 h. After 4-octyne (110 mg, 1.0 mmol) was added, the reaction mixture was

allowed to warm up to 0 °C. Zirconacyclopentene **11a** (R^1=R^2=C_3H_7) was yielded in ca. 90% based on 4-octyne after 3h. Allyl phenyl ether (168 mg, 1.25 mmol) was then added and the mixture was stirred for 3 h at 50 °C. After quenching with 3N HCl, the usual workup gave the title compound in 91% yield. Yields were determined by GC. The product was characterized by ^{1}H and ^{13}C NMR, GC-MS and high resolution mass spectroscopy, and compared with an authentic sample prepared by a known method.

(*E*)-5-Allyl-5-decene. The title compound was prepared in a similar manner to the case of (*E*)-4-allyl-4-octene using 5-decyne and allyl trimethylsilyl ether, instead of 4-octyne and allyl phenyl ether. Yield 97% (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.85-0.95 (m, 6H), 1.2-1.4 (m, 8H), 1.9-2.1 (m, 4H), 2.71 (dd, ^3J = 6.9 Hz, ^4J = 1 Hz, 2H), 4.95-5.10 (m, 2H), 5.14 (t, J = 7.3 Hz, 1H), 5.76 (ddt, J = 17, 10.2, 6.9 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.08, 14.08, 22.50, 22.84, 27.58, 29.87, 30.62, 32.34, 41.62, 115.36, 126.18, 137.63, 137.73.

5-Propyl-4,7-tridecadiene; (4E,7E)/(4E,7Z) = 34:66 mixture. The reaction was carried out in a similar manner to that described above, using 3-benzyloxyoct-1-ene instead of allyl phenyl ether. Yield 60% (GC). ^{1}H NMR ($CDCl_3$, Me_4Si, as a mixture of (4*E*,7*E*)/(4*E*,7*Z*)): δ 0.86-0.94 (m), 1.22-1.44 (m), 1.93-2.07 (m), 2.64 (d, 2H, J = 5.0 Hz, *E-isomer*), 2.71(d, 2H, J = 6.6 Hz, *Z-isomer*), 5.10-5.20 (m), 5.29-5.50(m). ^{13}C NMR ($CDCl_3$, Me_4Si, as a mixture of (4*E*,7*E*)/(4*E*,7*Z*)): δ 13.91, 14.11, 14.18, 21.44, 21.55, 22.57, 22.61, 23.22, 27.12, 29.27 29.42, 29.92, 31.41, 31.59, 32.17, 32.40, 32.52, 34.72, 40.36, 125.39, 125.55, 128.03, 128.68, 130.85, 131.75, 138.22, 138.56. High resolution mass spectroscopy; calcd for $C_{16}H_{30}$: 222.2348, found: 222.2353.

Allylation reactions of alkynes with allylic chlorides; Representative procedure; (2*E*,5*E*)-5-*n*-butyl-2,5-decadiene. To a solution of Cp_2ZrCl_2 (365 mg, 1.25 mmol) in THF (5 mL) was added ethylmagnesium bromide (0.9 M THF solution, 2.5 mmol) at -78 °C. After stirring for 1h at the same temperature, 5-decyne (138 mg, 1.0 mmol) was added and the reaction mixture was allowed to warm up to room temperature. The mixture was stirred for 1h, and then was added 3-chloro-1-butene (135 mg, 1.5 mmol) and stirred for an additional hour at 50 °C. The reaction mixture was quenched with 3N HCl, washed with $NaHCO_3$ and dried over $MgSO_4$. Filtration followed by concentration and bulb-to-bulb distillation gave the title compound (yield 48% by GC) accompanied by 5% of a stereoisomer. Ratio of stereoisomers 2*E*/2*Z* was 91:9. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.89 (t, J = 6.9 Hz, 3H), 0.90 (t, J = 6.9 Hz, 3H), 1.2-1.4 (m, 8H), 1.65-1.70 (m, 3H), 1.95-2.05 (m, 4H), 2.60-2.65 (m, 2H), 5.11 (t, J = 7.3 Hz, 1H), 5.35-5.45 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.05, 14.05, 17.92, 22.48, 22.82, 27.55, 29.79, 30.58, 32.36, 40.34, 125.51, 125.86, 129.91, 138.56. IR (cm^{-1}): 2959(s), 2928(s), 2874(s), 2861(s), 1458(m), 1379(m), 968(s). High resolution mass spectroscopy; calcd for $C_{14}H_{26}$: 194.2035, found: 194.2042.

(1*E*,4*E*)-2-Methyl-1-phenyl-1,4-hexadiene/(2*Z*,5*E*)-3-phenyl-2,5-heptadiene. The reaction was carried out in a similar manner to that described above using 1-phenyl-1-propyne

(116 mg, 1.0 mmol) instead of 5-decyne. Usual workup gave a mixture of isomers in 78% combined yield by GC. *(1E,4E)-2-Methyl-1-phenyl-1,4-hexadiene.* ^{1}H NMR ($CDCl_3$, Me_4Si): δ 1.70 (d, J = 4.3 Hz, 3H), 1.83 (d, J = 1 Hz, 3H), 2.82 (d, J = 4.3 Hz, 2H), 5.45-5.60 (m, 2H), 6.27 (s, 1H), 7.1-7.3 (m, 5H). 13C : 1.57 (d, J =7.3 Hz, 3H), 1.60-1.65 (m, 3H), 2.95-3.05 (m, 2H), 5.45-5.60 (m, 3H), 7.1-7.3 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 17.86, 17.95, 43.59, 125.21, 125.60, 126.92, 127.96, 128.82, 128.88, 138.22, 138.62. *(2Z,5E)-3-phenyl-2,5-heptadiene.* ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.72, 17.90, 42.08, 121.36, 126.34, 126.34, 127.65, 128.88, 129.04, 140.63, 141.27. High resolution mass spectroscopy calcd for $C_{13}H_{16}$ 172.1252, found: 172.1246.

(1Z,4E)-1,2-Diphenyl-1,4-hexadiene. The title compound was obtained in 79% yield by GC. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 1.65-1.70 (m, 3H), 3.14 (d, J = 1.3 Hz, 2H), 5.45-5.55 (m, 2H), 6.41 (s, 1H), 6.9-7.3 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 17.95, 43.49, 126.14, 126.56, 126.84, 127.26, 127.80, 128.25, 128.41, 128.55, 129.02, 137.48, 141.56, 142.12. IR (cm^{-1}): 3023(m), 2966(m), 2932(m), 1599(m), 1493(m), 968(m), 756(m), 696(s). High resolution mass spectroscopy; calcd for $C_{18}H_{18}$: 234.1409, found: 234.1409.

Reaction of Cp_2Zr(1,2-diphenylacetylene)(PMe_3) with allyl acetate, (Z)-1,2-diphenyl-1,4-pentadiene. Cp_2Zr(1,2-diphenylacetylene)(PMe_3) was prepared in the same way as described above from Cp_2ZrCl_2/2eq *n*-BuLi (Negishi reagent), 1,2-diphenylacetylene and trimethylphosphine. To a solution of this complex (1.25 mmol) in THF (5 mL) was added allyl acetate (150 mg, 1.5 mmol) and the mixture was stirred for 5h at 50 °C. Hydrolysis and the usual workup gave the title compound in 75% yield (by GC).

Reaction of 11a with 2,5-dihydrofuran, (*E*)-2-Vinyl-3-propylhept-3-en-1-ol (9a). Zirconacyclopentene **11a** was prepared in a similar manner to that described above. 2,5-Dihydrofuran (70 mg, 1.0 mmol) was added to a THF solution of **11a** (1.0 mmol) and the mixture was warmed up to 60 °C. After stirring for 3h, hydrolysis with 3N HCl and the usual workup gave the **9a** in 75% yield (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.90 (t, J = 7.3 Hz, 6H), 1.30-1.46 (m, 4H), 1.48-1.60 (m, 1H), 1.95-2.07 (m, 4H), 2.80-2.90 (m, 1H), 3.49-3.70 (m, 2H), 5.08-5.15 (m, 2H), 5.22 (t, J = 7.3 Hz, 1H), 5.66-5.81 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.87, 14.29, 22.23, 23.11, 29.90, 32.40, 53.01, 63.95, 116.31, 127.40, 138.25, 138.70. High resolution mass spectroscopy; calcd for $C_{12}H_{22}O$: 182.1671, found: 182.1671.

Allylation of 1-(trimethylsilyl)-1-hexyne via zirconacyclopentadiene 12a. To a solution of Cp_2ZrCl_2 (292 mg, 1.0 mmol) in THF was added *n*-butyllithium (1.6 M hexane solution, 2.0 mmol) at -78 °C and the mixture was stirred for 1 h at the same temperature. After adding 1-(trimethylsilyl)-1-hexyne (309 mg, 2.0 mmol), the reaction mixture was warmed up to room temperature and stirred for 1h. Zirconacyclopentadiene **12a** was formed quantitatively at this stage. Allyl trimethylsilyl ether (260 mg, 2.0 mmol) was then added to the solution of **12a**

and the mixture was stirred for 1h at 50 °C. Quenching the reaction mixture with 3N HCl and the usual workup gave (*E*)-4-*n*-butyl-1-(trimethylsilyl)-1,4-pentadiene **9b**. 85% yield (by GC).

Reactions of zirconocene-alkyne complexes with acetals: formation of vinyl ethers; Representative procedure; 4-*n*-hexyl-5-trimethylsilyl-1,4-pentadienyl ethyl ether (52:48 mixture of (1*E*,4*E*)/(1*Z*,4*E*)). To a solution of Cp_2ZrCl_2 (1.0 mmol, 292 mg) in THF (5 mL) was added *n*-butyllithium (1.6M hexane solution, 2.0 mmol) at -78 °C and stirred for 1h. After adding trimethylphosphine (1.0M in THF, 1.1 mmol) the reaction mixture was warmed up to room temperature and was stirred for 1h. Addition of 1-(trimethylsilyl)-1-octyne (1.0 mmol, 182 mg) gave zirconocene(1-(trimethylsilyl)-1-octyne)(PMe_3) complex in 90-95% yield after 2h. To this reaction mixture, acrolein diethyl acetal (2.0 mmol, 260 mg) was added and the mixture was stirred at 35 °C for 1h. After hydrolysis and the usual workup, the title compound was obtained in 75% yield with >98% of regioselectivity for Me_3Si and C_6H_{13} groups. ^1H NMR ($CDCl_3$, Me_4Si, as a (1*E*,4*E*)/(1*Z*,4*E*) mixture 52:48): δ 0.09 (s), 0.85-0.91 (m), 1.21-1.30 (m), 2.08-2.14 (m), 2.66 (d, 2H, *J* = 7.6 Hz, 1*E-isomer*), 2.86 (d, 2H, *J* = 7.3 Hz, 1*Z-isomer*), 3.70-3.83 (m), 4.37 (q, 1H, *J* = 6.3 Hz, 1*Z-isomer*), 4.75 (dt, 1H, *J* = 12.5, 6 Hz, 1*E-isomer*), 5.22 (s), 5.99-6.02 (m, 1H, 1*Z-isomer*), 6.21 (d, 1H, *J* = 12.5 Hz, 1*E-isomer*). ^{13}C NMR ($CDCl_3$, Me_4Si, as a (1*E*,4*E*)/(1*Z*,4*E*) mixture 52:48): δ 0.41, 14.09, 14.81, 15.29, 22.64, 29.06, 29.11, 29.63, 31.84, 33.53, 36.06, 36.33, 37.18, 64.67, 67.51, 102.03, 104.80, 122.59, 123.14, 145.26, 147.10, 159.17, 159.46. High resolution mass spectroscopy; calcd for $C_{16}H_{32}OSi$: 268.2222, found: 268.2232.

4-phenyl-5-trimethylsilyl-1,4-pentadienyl ethyl ether (47:53 mixture of (1*E*,4*E*) /(1*Z*,4*E*)). Yield 71% (by GC). ^1H NMR ($CDCl_3$, Me_4Si): δ –0.01-0.01 (m), 1.37 (t, *J* = 7 Hz, 3H), 1.44 (t, *J* =7 Hz, 3H), 3.14-3.18 (m, 2H, 1*E-isomer*), 3.36-3.41 (m, 2H, 1*Z-isomer*), 3.86-3.95 (m), 4.56-4.64 (m, 1H, 1*Z-isomer*), 4.92-5.04 (m, 1H, 1*E-isomer*), 5.78-5.81 (m), 6.15-6.20 (m, 1H, 1*Z-isomer*), 6.38 (d, *J* = 13 Hz, 1H, 1*E-isomer*), 7.3-7.7 (m). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 0.09, 0.13, 14.77, 15.26, 36.66, 40.50, 64.73, 67.53, 101.13, 103.83, 126.31, 126.74, 126.81, 126.88, 127.60, 127.74, 127.96, 128.01, 128.19, 131.97, 145.53, 147.53, 158.24, 158.96. High resolution mass spectroscopy; calcd for $C_{16}H_{24}OSi$: 260.1596, found 260.1586.

4-Methyl-5-trimethylsilyl-1,4-pentadienyl ethyl ether (59:41 mixture of (1*E*,4*E*) /(1Z,4E)). 72% combined yield. Regioselectivity for Me_3Si and CH_3 groups was 89%. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.09 (s), 1.20-1.30 (m), 1.76 (s, 1H, *E-isomer*), 1.78 (s, 1H, *Z-isomer*), 2.64 (d, 2H, *J* = 7.6 Hz, *E-isomer*), 2.84 (d, 2H, *J* = 7.3 Hz, *Z-isomer*), 3.69-3.82(m), 4.35-4.41 (m, 1H, *Z-isomer*), 4.77 (dt, 1H, *J* = 12.5, 7.6 Hz, *E-isomer*), 5.24 (s), 6.02 (d, 1H, *J* = 6.3 Hz, *Z-isomer*), 6.22 (d, 1H, *J* = 12.5 Hz). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 0.09, 14.79, 15.29, 21.47, 21.67, 36.77, 40.63, 64.65, 67.55, 101.78, 104.40, 122.37, 123.02, 145.41,

147.20, 154.36, 154.70. High resolution mass spectroscopy; calcd for $C_{11}H_{22}OSi$: 198.1440, found: 198.1435.

Reactions of zirconacyclopentenes with acetals; Formation of 4-propyl-1,4-octadienyl ethyl ether (51:49 mixture of (1*E*,4*E*)/(1*Z*,4*E*)). Zirconacyclopentane **11a** (R^1=R^2=C_3H_7) was prepared in a similar manner to that shown above. To this **11a** in THF was added acrolein diethyl acetal and the mixture was stirred for 48h at room temperature. Hydrolysis of the reaction mixture and the usual workup gave the title compound in 61% yield (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.85-0.92 (m), 1.20-1.54 (m), 1.93-2.02 (m), 2.57 (d, 2H, *J* = 7.3 Hz, 1*E-isomer*), 2.74-2.78 (m, 2H, *Z-isomer*), 3.66-3.81 (m), 4.30-4.39 (m, 1H, 1*Z-isomer*), 4.72 (dt, 1H, *J* = 12.5 Hz, *J* = 5.5 Hz, 1*E-isomer*), 5.13-5.20 (m), 5.97 (dt, 1H, *J* = 6.3 Hz, *J* = 1.3 Hz, 1*Z-isomer*), 6.20 (d, 1H, *J* = 12.5 Hz, 1*E-isomer*). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.96, 14.20, 14.84, 15.35, 21.56, 23.31, 23.34, 30.03, 31.54, 32.13, 32.34, 35.38, 64.55, 67.51, 102.59, 105.57, 124.85, 125.35, 138.70, 139.00, 145.08, 146.77.

Reactions of zirconacyclopentenes with homoallylic bromides; Representative procedure; 2-(cyclopropylmethyl)-1-phenyl-1-heptene. Typical procedure for the reactions of zirconacyclopentenes **11** with 4-bromo-1-butene is as follows. To a solution of zirconocene dichloride (365 mg; 1.25 mmol) in THF (3 mL) was added THF solution of ethylmagnesium bromide (1.04 M, 2.5 mmol) at -78 °C and the mixture was stirred for 1 h. After 1-phenyl-1-heptyne (173 mg, 1.0 mmol) was added the reaction mixture was allowed to warm up to 0 °C and stirred for 2 h. And then 4-bromo-1-butene (204 mg, 1.5 mmol) was added and the reaction mixture was stirred at 40 °C for 12 h. Quenching of the sample with 3N HCl and the usual workup gave the title compound in 68% yield by GC. The product was characterized by ^{1}H and ^{13}C NMR, GC-MS and high resolution mass spectroscopy. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.08-0.16 (m, 2H), 0.48-0.56 (m, 2H), 0.80-0.95 (m, 1H), 0.87 (t, *J* = 6.9 Hz, 3H), 1.20-1.36 (m, 4H), 1.42-1.54 (m, 2H), 2.06 (dd, *J* = 6.8, 1.1 Hz, 2H), 2.26 (dd, *J* = 9.6, 7.0 Hz, 2H), 6.39 (s, 1H), 7.14-7.33 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 5.53, 10.45, 14.84, 23.28, 28.89, 31.89, 32.80, 42.81, 125.34, 126.55, 128.78, 129.42, 139.52, 144.52. High resolution mass spectroscopy; calcd for $C_{17}H_{24}$: 228.1881, found: 228.1878.

(*E*)-4-(Cyclopropylmethyl)-4-octene. Yield 68% by GC. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.01-0.08 (m, 2H), 0.40-0.48 (m, 2H), 0.68-0.83 (m, 1H), 0.84-0.96 (m, 6H), 1.25-1.54 (m, 4H), 1.87 (d, *J* = 6.9 Hz, 2H), 1.97-2.10 (m, 4H), 5.23 (t, 1H, *J* = 7.3 Hz). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.64, 9.90, 13.91, 14.21, 21.65, 23.32, 29.83, 32.56, 41.83, 124.81, 139.37. High resolution mass spectroscopy; calcd for $C_{12}H_{22}$: 166.1720, found: 166.1722.

(*Z*)-4-(Cyclopropylmethyl)-5-iodo-4-octene. Yield 50% by GC. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.16-0.23 (m, 2H), 0.41-0.48 (m, 2H), 0.76-0.95 (m, 7H), 1.32-1.50 (m, 2H), 1.52-1.64 (m, 2H), 2.21 (d, *J* = 6.6 Hz, 2H), 2.24-2.30 (m, 2H), 2.51 (t, *J* = 7.4 Hz, 2H). ^{13}C

NMR ($CDCl_3$, Me_4Si): δ 4.28, 9.81, 12.92, 14.12, 22.03, 23.07, 33.84, 43.04, 46.54, 105.16, 144.18. High resolution mass spectroscopy; calcd for $C_{12}H_{21}I$: 292.0690, found: 292.0688.

(*E*)-4-(2-Methylcyclopropyl)methyl-4-octene. The title compound was obtained as a 74:26 mixture of cis:trans isomers of the cyclopropane ring. Yield 64% by GC. ^1H NMR ($CDCl_3$, Me_4Si): δ -0.28 (q, J = 4.3 Hz, 1H, *cis*), 0.14-0.22 (m, 2H, *trans*), 0.37-0.48 (m, 2H, *trans*), 0.59-0.69 (m, 1H, *cis*), 0.70-0.83 (m, 2H, *cis*), 0.85-0.93 (m, 6H, *both isomers*), 1.01 (d, J = 5.7 Hz, 3H, *cis*), 1.02 (d, J = 8.9 Hz, 3H, *trans*), 1.29-1.55 (m, 4H, *both isomers*), 1.83-2.10 (m, 6H, *both isomers*), 5.20 (t, J = 6.9 Hz, 1H, *trans*), 5.27 (t, J = 6.9 Hz, 1H, *cis*). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 9.56, 12.09, 12.94, 13.01, 13.26, 13.91, 14.21, 14.36, 18.74, 18.96, 21.62, 21.71, 23.32, 29.79, 29.85, 32.54, 32.72, 35.35, 41.40, 124.42, 124.54, 139.42, 139.57. High resolution mass spectroscopy; calcd for $C_{13}H_{24}$: 180.1876, found: 180.1878.

(*E*)-4-(2-Ethylcyclopropyl)methyl-4-octene. The title compound was obtained as a 26:74 mixture of cis:trans isomers of the cyclopropane ring. Yield 59% by GC. ^1H NMR ($CDCl_3$, Me_4Si): δ -0.26 (q, J = 4.0 Hz, 1H, *cis*), 0.15-0.22 (m, 2H, *trans*), 0.34-0.52 (m, 2H, *trans*), 0.61-0.81 (m, 3H, *cis*), 0.85-1.03 (m, 9H, *both isomers*), 1.12-1.45 (m, 6H, *both isomers*), 1.77-2.09 (m, 6H, *both isomers*), 5.21 (t, J = 6.9 Hz, 1H, *trans*), 5.23 (t, J = 7.6 Hz, 1H, *cis*). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 10.89, 11.64, 13.71, 13.91, 14.21, 14.47, 14.61, 17.54, 17.83, 20.77, 21.60, 21.67, 21.94, 23.32, 27.28, 29.81, 29.87, 32.47, 32.67, 35.54, 41.44, 124.47, 124.63, 139.48, 139.58. High resolution mass spectroscopy; calcd for $C_{14}H_{26}$: 194.2035, found: 194.2043.

(*E*)-3-(Cyclopropylmethyl)-3-hexene. Yield 70% by GC. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.01-0.07 (m, 2H), 0.41-0.46 (m, 2H), 0.68-0.85 (m, 1H), 0.956 (t, J = 7.6 Hz, 3H), 0.964 (t, J = 7.6 Hz, 3H), 1.88 (d, J = 6.6 Hz, 2H), 1.95-2.12 (m, 4H), 5.19 (t, J = 7.1 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.64, 9.85, 13.35, 14.81, 20.81, 23.41, 41.46, 125.82, 140.55.

(*E*)-3-(Cyclopropylmethyl)-4-deuterio-3-hexene. Yield 70% by GC with 95% D incorporation. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.01-0.07 (m, 2H), 0.41-0.48 (m, 2H), 0.70-0.90 (m, 1H), 0.956 (t, J = 7.6 Hz, 3H), 0.962 (t, J = 7.6 Hz, 3H), 1.88 (d, J = 7.0 Hz, 2H), 1.98-2.12 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.62, 9.81, 13.33, 14.79, 20.68, 23.38, 41.37, 125.44 (t, $|^1J_{CD}|$ = 23 Hz), 140.45.

(Z)-3-Cyclopropyl-1,2-diphenyl-1-propene. Yield by 80% by GC (78% isol.). ^1H NMR ($CDCl_3$, Me_4Si): δ 0.07-0.13 (m, 2H), 0.40-0.50 (m, 2H), 0.76-0.93 (m, 1H), 2.35 (dd, J = 7.0, 1.3 Hz, 2H), 6.52 (s, 1H), 6.89-7.31 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.71, 9.70, 45.43, 125.84, 126.04, 126.74, 127.78, 128.43, 128.48, 129.02, 137.54, 141.90, 143.27. High resolution mass spectroscopy; calcd for $C_{18}H_{18}$: 234.1409, found: 234.1415.

(Z)-3-Cyclopropyl-1-deuterio-1,2-diphenyl-1-propene. Yield 71% by GC with 94% D incorporation. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.07-0.12 (m, 2H), 0.42-0.49 (m, 2H), 0.76-0.90 (m, 1H), 2.35 (d, J = 6.9 Hz, 2H), 6.90-7.31 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ

4.71, 9.67, 45.36, 125.47 (t, $|^1J_{CD}|$ = 23 Hz), 126.04, 126.73, 127.77, 128.42, 128.45, 128.97, 137.43, 141.88, 143.16. High resolution mass spectroscopy; calcd for $C_{18}H_{17}D$: 235.1471, found: 235.1481.

(*E*)-3-Cyclopropyl-2-methyl-1-phenyl-propene. The title compound was obtained in 72% yield by GC with 13% yield of regioisomer. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.11-0.17 (m, 2H), 0.48-0.55 (m, 2H), 0.80-0.92 (m, 1H), 1.91 (d, *J* = 1.3 Hz, 3H), 2.06 (dd, *J* = 6.9, 0.6 Hz, 2H), 6.36 (s, 1H), 7.14-7.35 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.65, 9.70, 18.20, 45.34, 124.47, 125.77, 128.00, 128.89, 138.70, 139.30. High resolution mass spectroscopy; calcd for $C_{13}H_{16}$: 172.1252, found: 172.1259.

1-Cyclopropyl-2-nonene/1-cyclopropyl-2-methylene-octane, (77:23 mixture). Combined yield 59% (by GC). ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.01-0.11 (m), 0.37-0.51 (m, 2H), 0.64-0.82 (m), 0.88 (t, *J* = 6.3 Hz), 1.27-1.55 (m), 1.90 (d, *J* = 6.6 Hz), 1.97-2.08 (m), 4.71 (d, *J* = 1 Hz), 4.84 (s), 5.38-5.50 (m). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.04, 4.64, 9.52, 10.66, 14.11, 22.66, 27.82, 28.88, 29.15, 29.60, 31.77, 32.65, 36.42, 37.27, 41.02, 108.48, 129.07, 130.74, 150.28. High resolution mass spectroscopy; calcd for $C_{12}H_{22}$: 166.1722, found: 166.1717.

Reaction of a zirconacyclopentene with 4-bromo-1-butene, formation of the intermediate 21. To a solution of zirconocene dichloride (365 mg; 1.25 mmol) in THF (3 mL) was added THF solution of ethylmagnesium bromide (1.04 M, 2.5 mmol) at -78 °C and the mixture was stirred for 1h. After 1-phenyl-1-heptyne (173 mg, 1.0 mmol) was added the reaction mixture was allowed to warm up to 0 °C and stirred for 2 h. Then 4-bromo-1-butene (204 mg, 1.5 mmol) was added and the reaction mixture was stirred at 40 °C for 12 hours. Addition of 15 mL of hexane to the reaction mixture lead to the precipitation of Mg salts. The clear solution was transferred to another Schlenk tube and pumped off. The remaining oil was dissolved in benzene and treated with MeLi (1.05 M in ether, 0.4 mmol) at 0 °C. The reaction mixture was allowed to warm up to the room temperature and NMR analysis showed the formation of $Cp_2Zr(Me)$(2-(cyclopropylmethyl)-1-phenyl-1-heptenyl) **21** in 93% yield by ^{1}H NMR. ^{1}H NMR (THF-d_8, Me_4Si): δ -1.19 (s, 3H), 0.17-0.20 (m, 2H), 0.50-0.55 (m, 2H), 0.78 (t, *J* = 7 Hz, 3H), 0.7-0.9 (m, 1H), 1.0-1.5 (m, 6H), 1.6-2.0 (m, 4H), 5.99 (s, 10H), 7.0-7.2 (m, 5H). ^{13}C NMR (THF-d_8, Me_4Si) δ 5.34, 10.53, 14.12, 22.96, 25.97, 29.22, 32.69, 34.03, 43.02, 109.27, 125.41, 128.39, 130.62, 143.47, 143.70.

Vinylzirconation Reactions of Internal Alkynes. Typical procedure is as follows. To a solution of zirconocene dichloride (0.365 g, 1.25 mmol) in 3.5 mL of THF was added ethylmagnesium bromide (1.0 M THF solution, 2.5 mL, 2.5 mmol) at -78 °C and the mixture was stirred for 1 h. After addition of 4-octyne (0.110 g, 1.0 mmol) the reaction mixture was allowed to be warmed up to 0 °C and stirred at 0 °C for 2 hours. To this ethyl vinyl ether (144 mg, 2.0 mmol) was added and the reaction mixture was stirred at 50 °C for 6 hours. Quenching

of the sample with 3N HCl gave 3-propyl-1,3-heptadiene in 88% yield. Quenching of reaction mixture with iodine (0.5 g, 2 mmol) afforded 4-iodo-3-propyl-1,3-heptadiene in 90% yield. All products were characterized by ^{1}H and ^{13}C NMR, GC-MS and High resolution mass spectroscopy.

3-Propyl-1,3-heptadiene: ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.92 (t, J = 7.3 Hz, 3H), 0.93 (t, J = 7.5 Hz, 3H), 1.33-1.53 (m, 4H), 2.10 (q, J = 7.4 Hz, 2H), 2.17-2.23 (m, 2H), 4.90 (d, J = 11.2 Hz, 1H), 5.09 (d, J = 17.5 Hz, 1H), 5.46 (t, J = 7.3 Hz, 1H), 6.26 (dd, J = 10.7 Hz, J = 17.5 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.98, 14.36, 22.17, 22.88, 28.27, 30.31, 110.15, 133.46, 138.54, 140.61. MS (EI) *m/e* 138 (M^+). High resolution mass spectroscopy; calcd for $C_{10}H_{18}$: 138.1409, found: 138.1410.

4-Iodo-3-propyl-1,3-heptadiene: ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.93 (t, J = 7.3 Hz, 3H), 0.94 (t, J = 7.6 Hz, 3H), 1.36-1.50 (m, 2H), 1.54-1.68 (m, 2H), 2.31-2.38 (m, 2H), 2.61-2.68 (m, 2H), 5.13 (d, J = 10.9 Hz, 1H), 5.25 (d, J = 17.5 Hz, 1H), 6.65 (dd, J = 10.9 Hz, J = 17.5 Hz, 1H). ^{13}C NMR (C_6D_6, Me_4Si): δ 13.12, 14.16, 22.48, 23.09, 30.58, 43.97, 111.27, 116.08, 140.32, 143.07. MS (EI) *m/e* 264 (M^+). High resolution mass spectroscopy; calcd for $C_{10}H_{17}I$: 264.0375, found: 264.0370.

1,2-Diphenyl-1,3-butadiene : ^{1}H NMR ($CDCl_3$, Me_4Si): δ 4.83 (d, J = 17.2 Hz, 1H), 4.13 (d, J = 10.9 Hz, 1H), 6.58 (s, 1H), 6.71 (ddd, J = 0.7 Hz, J = 10.2 Hz, J = 17.2 Hz, 1H), 6.86-7.39 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 116.20, 127.13, 127.55, 128.14, 129.00, 129.74, 130.00, 131.84, 137.14, 138.47, 142.14 , 142.23. MS (EI) *m/e* 206 (M^+). High resolution mass spectroscopy; calcd for $C_{16}H_{14}$: 206.1096, found: 206.1104.

1-Iodo-1,2-diphenyl-1,3-butadiene (as a mixture of E/Z isomers 1:1): ^{1}H NMR ($CDCl_3$, Me_4Si): δ 4.70 (d, J = 17.2 Hz, 1H), 4.93 (d, J = 17.2 Hz, 1H), 5.06 (d, J = 10.9 Hz, 1H), 5.36 (d, J = 10.6 Hz, 1H), 6.59 (dd, 1H, J = 10.5 Hz, J = 16.5 Hz), 6.93-7.46 (m, 21 H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 104.09, 105.42, 120.24, 123.21, 127.75, 128.06, 128.29, 128.38, 128.60, 129.00, 129.03, 129.17, 130.18, 130.31, 130.50, 131.22, 135.05, 138.16, 144.20, 144.38, 144.52, 145.09, 146.91, 149.19. MS (EI) *m/e* 332 (M^+). High resolution mass spectroscopy; calcd for $C_{16}H_{13}I$: 332.0062 found: 332.0064.

1-Phenyl-2-pentyl-1,3-butadiene: ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.89(t, J = 6.6 Hz, 3H), 1.25-1.46 (m, 4H), 1.50-1.60 (m, 2H), 2.39-2.47 (m, 2H), 5.11 (d, J = 10.9 Hz, 1H), 5.30 (d, J = 17.2 Hz, 1H), 6.41(dd, J = 10.9 Hz, J = 17.4 Hz, 1H), 6.46 (s, 1H), 7.09-7.35 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.09, 22.44, 26.88, 28.84, 32.24, 112.76, 126.63, 128.21, 128.75, 131.21, 137.70, 140.88, 141.02. MS (EI) *m/e* 200 (M^+). High resolution mass spectroscopy; calcd for $C_{15}H_{20}$: 200.1565, found: 200.1545.

***cis*-5-Propyl-3,5-nonadien-1-ol:** ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.89 (t, J = 7.6 Hz, 3H), 0.93 (t, J = 7.3 Hz, 3H), 1.30-1.45 (m, 4H), 1.67 (br s, 1H), 2.00-2.18 (m, 4H), 2.45-2.54 (m, 2H), 3.66 (t, J = 6.6 Hz, 2H), 5.31-5.46 (m, 2H), 5.93 (d, J = 10.9 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.96, 21.76, 23.07, 30.04, 32.08, 32.61, 62.89, 125.51, 130.06, 134.86,

136.28. MS (EI) *m/e* 182 (M^+). High resolution mass spectroscopy; calcd for $C_{12}H_{22}O$: 182.1671, found: 182.1665.

***trans*-5-Propyl-3,5-nonadien-1-ol** : ^1H NMR ($CDCl_3$, Me_4Si): δ 0.85-0.96 (m, 6H), 1.30-1.45 (m, 4H), 1.92-2.18 (m, 5H), 2.35 (q, J = 6.8 Hz, 2H), 3.65 (t, J = 6.7 Hz, 2H), 5.31-5.57 (m, 2H), 6.05 (d, J = 15.5 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.98, 14.38, 22.25, 22.95, 28.95, 30.26, 36.52, 62.19, 122.17, 132.02, 136.87, 137.82. MS (EI) *m/e* 182 (M^+).

Vinylzirconation of 1-Octyne. Typical procedure is as follows. To a suspension of zirconocene chloride hydride (0.258 g, 1.0 mmol) in 5 mL of THF was added 1-octyne (0.110 g, 1.0 mmol) at 0 °C and the mixture was stirred for 3 h. To the clear solution at -78 °C solution of methyl lithium in ether (1.0 M, 1 mL, 1 mmol) was added and the reaction mixture was stirred for 1h at -78 °C. And then ethyl vinyl ether (0.144 g, 2.0 mmol) was added and the reaction mixture was stirred at 35 °C for 6 hours. Quenching of the sample with 3N HCl gave 1,3-decadiene in 72 % yield. Quenching of reaction mixture with iodine (0.5 g, 2 mmol) produced 4-Iodo-1,3-decadiene in 57 %.

4-Iodo-1,3-decadiene: ^1H NMR ($CDCl_3$, Me_4Si): δ 0.89 (t, J = 7.0 Hz, 3H), 1.23-1.34 (m, 6H), 1.50-1.58 (m, 2H), 2.53 (t, J = 7.3 Hz, 2H), 5.24 (dd, J = 1.6 Hz, J = 10.2 Hz, 1H), 5.36 (dd, J = 1.6 Hz, J = 16.8 Hz, 1H), 6.13 (d, J = 9.6 Hz, 1H), 6.44 (dt, 1H, J = 9.9 Hz, J = 16.8 Hz). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.07, 22.55, 27.94, 29.36, 31.57, 45.57, 111.41, 119.50, 133.80, 139.15. MS (EI) *m/e* 264 (M^+). High resolution mass spectroscopy; calcd for $C_{10}H_{17}I$: 264.0375, found: 264.0381.

A Vinylzirconation Product 23b (R^1 = R^2 = Ph): ^1H NMR (C_6D_6, Me_4Si): δ 5.01 (dd, J = 17.4 Hz, J = 1.9 Hz, 1H), 5.28 (dd, 1H, J = 10.6 Hz, J = 1.6 Hz, 1H), 5.99 (s, 10H), 6.30 (dd, J = 17.2 Hz, J = 10.6Hz, 1H), 6.51 (dd, J = 8.1 Hz, J = 1.2 Hz, 1H), 6.75-7.30 (m, 9H). ^{13}C NMR (C_6D_6, Me_4Si): δ 110.42, 116.55, 126.05, 127.69, 128.82, 129.47, 129.59, 131.89, 141.85, 142.33, 147.24, 192.45.

Formation of 23b (R^1 =R^2 =Ph) from 11 and Ethyl Vinyl Ether Zirconacyclopentene **11** (R^1 = R^2 = Ph) (1.9 mmol) was dissolved in 10 mL of C_6D_6. After addition of ethyl vinyl ether (0.288 g, 4.0 mmol) the mixture was stirred at 50 °C for 3 h. The NMR analysis of the solution showed a clean formation of one zirconium complex **23b** in 83% yield (based on zirconacyclopentene, Cp peak at 5.99 ppm was used for the determination of the yield). Hydrolysis gave 1,2-Diphenyl-1,3-butadiene in 85% yield. **23b** (R^1 = R^2 = Ph) : ^1H NMR (C_6D_6, Me_4Si): δ 5.01 (dd, J = 17.4 Hz, J = 1.9 Hz, 1H), 5.28 (dd, J = 10.6 Hz, J = 1.6 Hz, 1H), 5.99 (s, 10H), 6.30 (dd, J = 17.2 Hz, J = 10.6Hz, 1H), 6.51 (dd, J = 8.1 Hz, J = 1.2 Hz, 1H), 6.75-7.30 (m, 9H). ^{13}C NMR (C_6D_6, Me_4Si): δ 110.42, 116.55, 126.05, 127.69, 128.82, 129.47, 129.59, 131.89, 141.85, 142.33, 147.24, 192.45.

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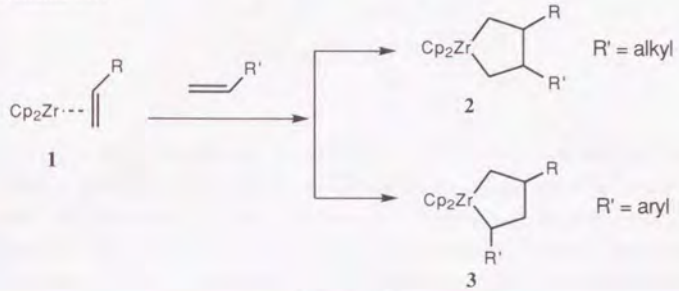
Chapter 5. Coupling of Alkenes with Ketones or Aldehydes on Zirconium

Abstract: Reactions of zirconocene-alkene complexes $Cp_2Zr(CH_2{=}CHR)(PR'_3)$ (R = H, Me, Et, SiR''_3 or Ar) with aldehydes or ketones were investigated. Zirconocene-ethylene, -propylene or 1-butene complexes reacted with aldehydes or ketones at terminal carbons of alkenes to give the corresponding alcohols after hydrolysis with a high regioselectivity. A similar type of reaction product was also obtained by a reaction of zirconacyclopentanes with aldehydes. This reaction proceeded via β-β' carbon-carbon bond cleavage of zirconacyclopentanes. A reaction of zirconocene-vinylsilane complexes with ketones afforded 3-trimethylsilyl-1-oxa-2-zirconacyclopentanes with an excellent regioselectivity. Carbon-carbon bond formation occurred exclusively at the terminal carbon of vinylsilanes. Their corresponding γ-silylalcohols were obtained after hydrolysis. The products showed that vinylsilanes reacted with carbonyl compounds at the β-carbon to silyl group. It is in sharp contrast to the conventional reactions of vinylsilanes of which the α-carbon normally attacked electrophiles. The reactions of styrene and its derivatives with pentan-3-one on zirconium gave a mixture of two regioisomers. Substituents of alkenes tend to be in α-position to Zr in 1-oxa-2-zirconacyclopentanes. This orientation showed a different aspect of the formation of 1-oxa-2-zirconacyclopentanes from the alkene-alkene coupling reaction on zirconium. The regioselectivity of the reaction with carbonyl compounds decreased in this order; R = alkyl > silyl > aryl.

Introduction

Recently Takahashi et al. reported a highly regioselective carbon-carbon bond formation reaction of zirconocene-alkene complexes **1** with alkenes giving zirconacyclopentanes **2** or **3**.[1] In these reaction products alkyl groups R and R' were in β-position of zirconacyclopentanes **2** with a >98% regioselectivity, whereas an aryl group R' was in α-position with a >98% regioselectivity as shown in Scheme 5.1.



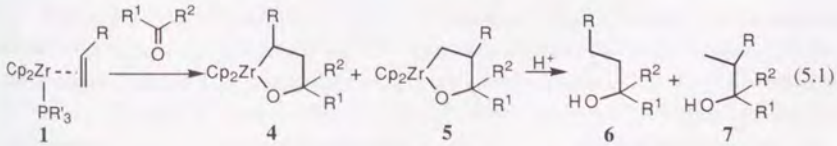
Scheme 5.1

In the course of further investigations of reactions of these zirconocene-alkene complexes, the author and co-workers found a regioselective carbon-carbon bond formation reaction of **1** with aldehydes or ketones. In this chapter I would like to describe the details of the reaction of zirconocene-alkene complexes with aldehydes or ketones with good to excellent selectivities and a reaction of a zirconacyclopentane with aldehydes which gave the same product.

Results and Discussion

Reaction of $Cp_2Zr(CH_2{=}CHR)(PMePh_2)$ (R=H, Me, Et) with aldehydes or ketones

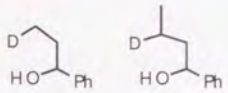
It was known that the reaction of zirconocene-stilbene complex[2] or -cyclobutene complexes[3] with acetone gave alcohols after hydrolysis. However, regioselectivity for the reaction of unsymmetrical alkenes have not been reported. As shown in eq 5.1 two regioisomers **6** and **7** are possible for unsymmetrical alkenes. Interestingly as shown in Table 5.1, zirconocene-propene or 1-butene complexes reacted with various aldehydes or ketones to give exclusively **6** after hydrolysis.[4]



(5.1)

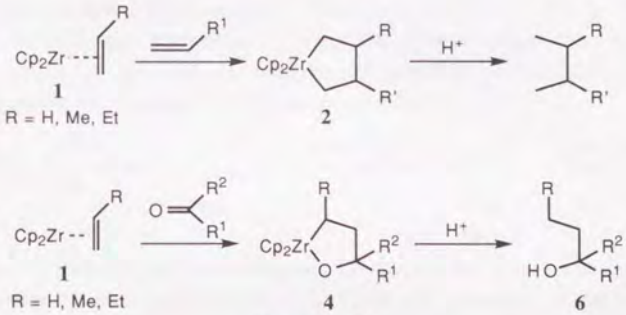
A reaction of a titanocene-ethylene complex with aldehydes has been reported.[5] The products, 1-oxa-2-titanacyclopentanes were fully characterized by X-ray analysis recently.[6] The structure of

zirconium analog, 1-oxa-2-zirconacyclopentane, has been also determined by X-ray analysis.[7] The reaction mechanism of the reaction of zirconocene-alkene complexes with aldehydes or ketones presumably involves the formation of 1-oxa-2-zirconacyclopentanes **4**. Indeed, deuterolysis of the reaction mixture gave **8** (R=H, R'=Ph) and **9** (R=CH_3, R'=Ph) with 85% and 94% D incorporation, respectively.



8 **9**

However, unfortunately, monitoring the reaction of **1a** (R=H) with benzaldehyde or 2-phenylpropanal in THF at room temperature by NMR spectroscopy did not show a clean formation of one species such as 1-oxa-2-zirconacyclopentanes. Interestingly, the orientation of alkenes observed here was opposite to that for the reaction of **1** with alkenes. Scheme 5.2 summarizes the difference in regioselectivities between the reactions of zirconium-alkene complexes with alkenes and with aldehydes or ketones.

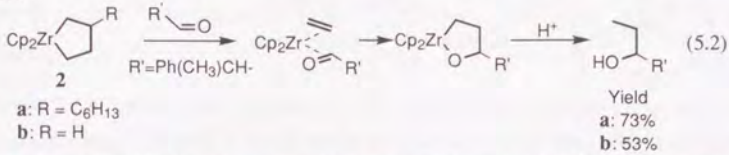


Scheme 5.2

Reactions of Zirconacyclopentanes with aldehydes

It was found that the treatment of zirconacyclopentanes with an aldehyde gave a coupling product of ethylene with the aldehyde (eq 5.2). Zirconacyclopentane **2a**,[8] prepared from Cp_2ZrEt_2 and 1-octene, reacted with 2-phenylpropanal to give 2-phenylpentan-3-ol in 73% yield after hydrolysis. This reaction can be explained by the β,β'-carbon-carbon bond activation,[9] followed by the formation of 1-oxa-2-zirconacyclopentanes as shown in eq 5.2. The reaction was highly "pair"-selective. Coupling product of 1-octene and 2-phenylpropanal, 4-methyl-2-phenyldecan-3-ol, was not detected. Zirconacyclopentane **2b**, which was prepared from Cp_2ZrCl_2 and $BrMg(CH_2)_4MgBr$,

also showed a similar reactivity in the presence of 2-phenylpropanal to afford the same product in 53% yield.

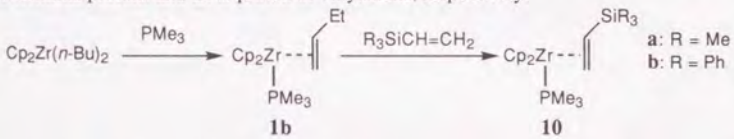


(5.2)

We recently reported the similar reactions of zirconacyclopentenes via β-β' carbon-carbon bond activation with unsaturated compounds such as aldehydes, ketones, nitriles, alkynes and homoallylic halides.[10,11]

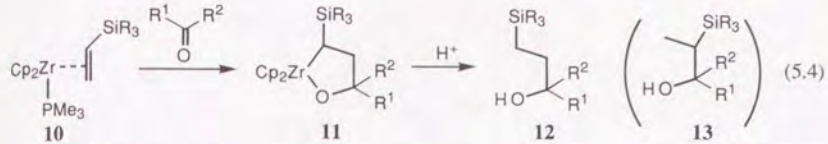
Reaction of $Cp_2Zr(CH_2{=}CHSiR_3)(PMe_3)$ with aldehydes or ketones

In order to investigate the effect of silyl group, I prepared zirconocene-vinylsilane complexes.[12] Zirconocene-vinylsilane complexes ($Cp_2Zr(CH_2{=}CHSiR_3)(PMe_3)$) **10** were cleanly formed (R=Me, 93% yield; R=Ph, 94% yield) by treatment of Cp_2ZrBu_2 (Negishi reagent) with vinylsilanes in the presence of trimethylphosphine (eq 5.3). Vinylsilanes displaced cleanly 1-butene in Cp_2Zr(1-butene)(PMe_3) **1b** which was formed from Cp_2ZrBu_2 in the presence of PMe_3.[13] The NMR spectrum of **10a** indicated that there were two isomers in a ratio of 85:15. The ^1H NMR spectrum of the major isomer showed two singlets at 5.14 and 5.22 ppm, two peaks (ddd) coupled with ^{31}P nucleus at 0.00 and 0.54 ppm, and one doublet of doublet at 0.08 ppm assignable to Cp protons, two terminal protons and an α-proton of vinylsilane, respectively.

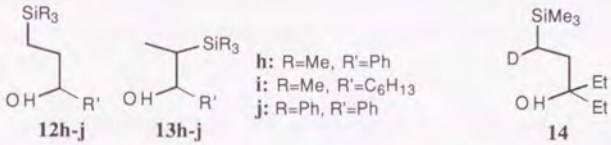


(5.3)

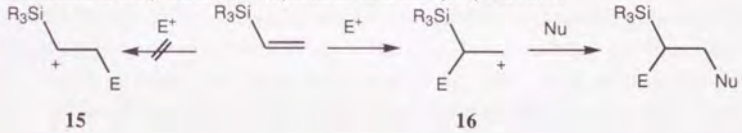
As shown in Table 5.2, reactions of **10a** with ketones provided 1-oxa-2-zirconacyclopentanes **11** in good yields in contrast to the reaction of **1**. In the case of the reaction with unsymmetrical ketones, a 1:1-2:1 mixture of diastereomers was obtained. In this reaction trimethylphosphine did not inhibit the reactions with ketones, although only weak donating ligands such as diphenylmethylphosphine could be used for the reaction of zirconocene-ethylene, propene or butene complexes. The products **11** were formed in a highly regioselective manner (>95%), with the silyl group in α-position of 1-oxa-2-zirconacyclopentane. This regioselectivity is similar to the case of the reaction of $Cp_2Zr(CH_2{=}CHR)(PMePh_2)$ (R = H, Me, Et) with aldehydes described above.



Trialkylsilyl groups were known to have a tendency to come to α-position of zirconacyclopentanes.[14] Formation of **11** with vinylsilane indicated the same orientation (eq 5.4).

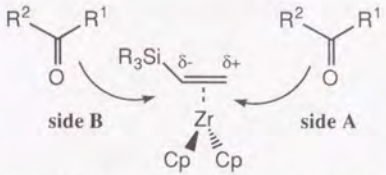


Hydrolysis of **11** gave the corresponding alcohols, providing a method to prepare γ-silylalcohols as shown in Table 5.2. Deuterolysis of **11** afforded **14** with >95% deuterium incorporation. As a general rule, electrophiles (E^+) attack the silicon-bearing carbon atom (α-carbon) of vinylsilanes, due to the β-silicon effect which stabilizes a structure **15** over **16** (Scheme 5.3).[15] On the other hand, when a vinylsilane was treated with organometallic reagents such as EtLi followed by a treatment with aldehydes, a carbon-carbon bond formation occurred at the α-carbon of vinylsilanes to give β-silylalcohols.[16] In our reaction with ketones, the carbon-carbon bond was formed at the β-carbon of vinylsilanes to afford γ-silylalcohols.



Scheme 5.3

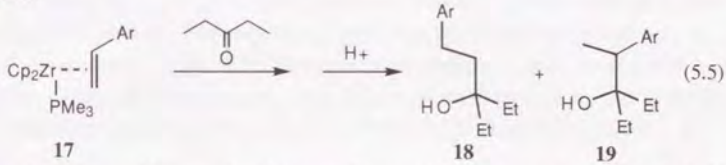
A reaction of **10a** (R = Me) with benzaldehyde and heptaldehyde, however, gave a mixture of two regioisomers of alcohols **12h-j** and **13h-j** with rather lower regioselectivities, 64% and 55%, respectively. Less bulky carbonyl compounds such as aldehydes were able to attack the vinylsilane on zirconium from trialkylsilyl side (side B) which is more hindered. Vinyltriphenylsilane complex **10b** (R = Ph) with a more bulky substituent, indeed, suppressed an aldehyde to attack from the silicon side. γ-Silylalcohol **12j**, which was a resultant of an attack from side A, was predominantly obtained (>94% regioselectivity) by the reaction of **10b** with benzaldehyde. It is of great interest in comparison with the result of the reactions of zirconocene-propylene or -butene complex with aldehydes which attacked from side A only. It is presumably due to polarized character of vinylsilane described above (Scheme 5.3). Anionic character of α-carbon stabilized by silyl group might facilitate a nucleophilic attack to carbonyl carbon.



To our interest, even triphenylsilyl moiety came to α-position to zirconium in 1-oxa-2-zirconacyclopentane **11** in spite of its bulkiness. A steric repulsion between an electrophile and a trialkylsilyl group on zirconocene-vinylsilane complexes seems to mainly govern the regioselectivity in the formation of **11**.

Reaction of $Cp_2Zr(CH_2{=}CHAr)(PMe_3)$ with pentan-3-one; Regioselectivity in the formation of 1-oxa-2-zirconacyclopentanes

Zirconocene-styrene complex **17** was prepared by a reaction of zirconocene-butene complex with styrene as previously reported.[13,17,18] This method could be applied for p-substituted styrene derivatives.

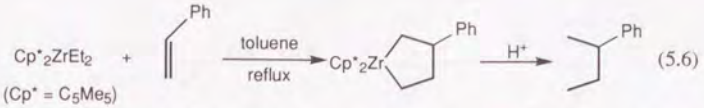


(5.5)

The complex **17** smoothly reacted with pentan-3-one to give the corresponding alcohols **18** and **19** after hydrolysis as a mixture of regioisomers. The results of the reactions of zirconocene-styrene complexes or its derivatives are summarized in Table 5.3. In contrast to the results on alkene complexes or vinylsilane complexes, relatively low regioselectivities were observed. Two factors can be taken into considerations for the regioselectivity during the formation of 1-oxa-2-zirconacyclopentanes. One is an electronic factor and the other is a steric factor. Despite a wide range of electronic character of substituents, the reactions of these p-substituted styrene complexes showed similar regioselectivities in the formation of corresponding alcohols. On the other hand, 2,4,6-trimethylstyrene, gave 1-(2,4,6-trimethylphenyl)-3-ethylpentan-3-ol (**18**) as a single product after hydrolysis. Bulky substituents remarkably improved its regioselectivity.

As to the formation of 1-oxa-2-zirconacyclopentanes, two kinds of steric repulsion can be considered. One is a repulsion between Cp ring and a substituent on alkenes, and the other is between an electrophile and a substituent of alkenes. The former might affect the stability of resultant zirconacycles. Indeed, we observed the former steric effect in the formation of a zirconacyclopentane. With pentamethylcyclopentadiene (Cp^*), sterically more hindered cyclopentadienyl ligands, a reaction of $Cp^*_2ZrEt_2$ with styrene led to the formation of 1-methylpropylbenzene after hydrolysis with >99% regioselectivity (eq 5.6, yield 38%) while

Cp_2ZrEt_2 gave exclusively butylbenzene. This is due to a steric repulsion between Cp* rings and a phenyl group.



(5.6)

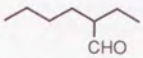
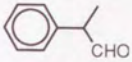
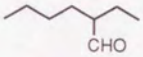
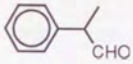
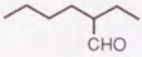
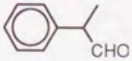
The formation of 1-oxa-2-zirconacyclopentanes presented here, however, revealed the latter steric effect. The result on the reaction of 2,4,6-trimethylstyrene obviously indicated that the steric factor between an aldehydes and an aryl group mainly controlled the regioselectivities in the formation of 1-oxa-2-zirconacyclopentanes. The electrophile attacked from the less hindered side of alkenes on zirconium to form new C-C bond as a result. It can also account for the regioselectivity in the reactions of zirconocene-propene or 1-butene complexes. Therefore the steric repulsion between a substituent and an electrophile seems to overcome that between Cp ligands and a substituent of alkenes. This aspect of the regioselectivity in the reaction of zirconocene-alkene complexes with carbonyl compounds is different from that in an alkene-alkene coupling reaction.

The regioselectivities in the reaction of zirconocene-alkene complexes with electrophiles were summarized in Table 5.4. Relatively higher regioselectivity in the case of propylene or 1-butene complex compared with the case of vinylsilane or styrene complexes cannot be explained by only the steric effect. Although all factors which control the regiochemistry were not clearly elucidated yet, the nucleophilicity of α-carbon of vinylsilanes or styrene might affect the factors.

Conclusion

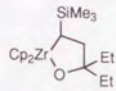
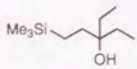
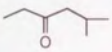
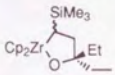
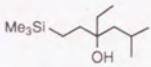
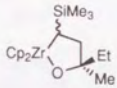
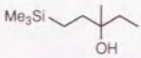
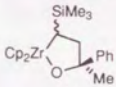
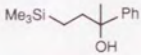
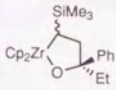
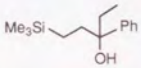
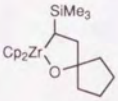
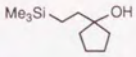
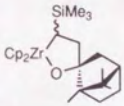
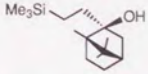
Zirconocene-alkene complexes $Cp_2Zr(CH_2{=}CHR)(PR'_3)$ reacted with aldehydes or ketones to form new carbon-carbon bonds at carbonyl carbons. Substituents on alkenes had a tendency to come to α-position in the formation of zirconacycles. The regioselectivity decreased in the order of R = alkyl > silyl > aryl as shown in Table 5.4. This showed a different aspect of regioselectivity from that of an alkene-alkene coupling reaction on zirconium. A steric repulsion between a substituent of alkenes and an electrophile has a stronger effect than that between Cp ligands and a substituent of alkenes.

Table 5.1. Reactions of $Cp_2Zr(CH_2{=}CHR)(PMePh_2)$ with aldehydes or ketones ($R = H, CH_3, CH_2CH_3$) .

R	Aldehyde or Ketone	Time/h	Yield/% [a]	Regioselectivity/% [b]	
				6	**7**
H	n-$C_7H_{15}CHO$	2	97	—	—
H		2	97	—	—
H		1	90	—	—
H	PhCHO	2	95	—	—
H		1	78	—	—
CH_3	n-$C_7H_{15}CHO$	2	71	>99	<1
CH_3		2	46	>99	<1
CH_3		3	48	>99	<1
CH_3	PhCHO	2	67	>99	<1
CH_3		1	40	>99	<1
C_2H_5	n-$C_7H_{15}CHO$	2	29	>99	<1
C_2H_5		2	64	>99	<1
C_2H_5		3	35	>99	<1

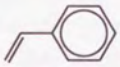
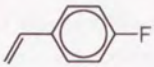
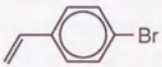
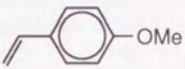
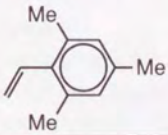
a), b) determined by GC and NMR spectroscopy.

Table 5.2. Formation of 2-Di(η^5-cyclopentadienyl)-3-trialkylsilyl-1-oxa-2-zirconacyclopentanes **11** and γ-Silylalcohols **12**

Ketone	1-Oxa-2-zircona-cyclopentane **11**	Yield of **11**[a] /%	γ-Silylalcohol **12**	Yield of **12**[b] /%	Regio-selectivity / %
	 **11a**	88		75	> 98
	 **11b**	71		60	> 95
	 **11c**	77		69	> 95
	 **11d**	87		72	> 97
	 **11e**	83		68	> 98
	 **11f**	85		75	> 97
	 **11g**	90		75	> 98[c]

a) by ^{1}H NMR b) isolated yield c) d.e. >99%

Table 5.3. Coupling Reactions of Zirconocene-Styrene Complexes with Pentan-3-one

Styrene derivative	Yield[a] %	Regioselectivity **18**:**19**
	84	63:37
	79	67:33
	83	69:31
	63	65:35
	63	68:32
	84	71:29
	62	>99:1

a) combined yield of **18** and **19**; determined by GC.

Table 5.4. Comparison of Regioselectivity in The Reaction of Zirconocene-Alkene Complexes with Electrophiles

	R in $Cp_2Zr(CH_2{=}CHR)(PR'_3)$		
	alkyl	silyl	aryl
ketones	>99%	>95-99 %	63-99 %
aldehydes	>99%	55-94 %	a

a) low yield

Experimental Section

General

All reactions involving organozirconium compounds were carried out under nitrogen. Tetrahydrofuran was dried over sodium diphenylketyl radical. Zirconocene dichloride and propylmagnesium chloride were purchased from Aldrich Chemical Company, Inc. Ethylmagnesium bromide (THF solution) and butyllithium (hexane solution) were purchased from Kanto Chemicals Co. Ltd. ^{1}H (270 MHz) and ^{13}C (67.5 MHz) NMR spectra were recorded on JEOL EX270 NMR spectrometer. Deuterium incorporation was determined by ^{13}C NMR spectra (gated decoupling pulse technique without NOE).

Reaction of $Cp_2Zr(CH_2{=}CHR)(PMePh_2)$ (R = H,Me,Et) with Aldehydes or Ketones Representative Procedure; Decan-3-ol

Diethylzirconocene was prepared in situ by adding ethylmagnesium bromide in THF (1.0 M, 2.0 mmol) to a solution of zirconocene dichloride (292 mg, 1.0 mmol) in THF (5 mL) at -78 °C. The mixture was stirred for 1 h at the same temperature. After addition of diphenylmethylphosphine (200 mg, 1.0 mmol) , the mixture was warmed up to room temperature and stirred for 1 h. To this reaction mixture containing the zirconocene-ethylene complex **1a** thus prepared in high yield was added octyl aldehyde (128 mg, 1.0 mmol). After the mixture was stirred for additional 2 h, the yellow solution was added 3 N HCl and extracted with ether. Usual work-up followed by bulb-to-bulb distillation gave decan-3-ol (97% yield). Yields were determined by GC. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, J = 7 Hz, 3H), 0.94 (t, J = 8 Hz, 3H), 1.29-1.53 (m, 14H), 3.52 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 9.88, 14.09, 22.68, 25.70, 29.32, 29.71, 30.18, 31.87, 37.01, 73.38.

4-Ethyloctan-3-ol

Reaction was carried out in a similar manner to the representative procedure using 2-ethylhexanal (128 mg, 1.0 mmol). The title compound was obtained in 97% yield as a 1/1 mixture of diastereomeric isomers. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.90 (t, J = 7 Hz, 3H), 0.94-0.98 (m, 6H), 1.28-1.51 (m, 11H), 3.52 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 10.65, 10.65, 11.83, 11.90, 14.08, 14.08, 21.61, 22.85, 23.16, 23.20, 26.90, 26.95, 28.35, 29.40, 29.72, 29.94, 44.81, 44.85, 75.04, 75.12.

2-Phenylpentan-3-ol

The title compound was obtained in 90% yield as a 2.7/1 mixture of diastereomeric isomers. For major product, (R,R)/(S,S)-2-Phenylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.9 (t, 3H, J = 7.4 Hz), 1.29 (d, 3H, J = 6.9 Hz), 1.3-1.5 (m, 2H), 2.7 (dq, 1H, J = 6.9Hz), 3.4-3.6 (m, 1H), 7.1-7.4 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ: 10.39, 15.81, 27.57, 45.41, 77.68, 126.29, 127.80, 128.39, 144.83. For minor product, (R,S)/(S,R)-2-Phenylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.97 (t, J = 7.4 Hz, 3H), 1.25 (t, J = 6.9 Hz, 3H), 1.3-1.5 (m, 2H), 2.6-2.8

(m, 1H), 3.4-3.6 (m, 1H), 7.1 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 10.50, 17.90, 27.17, 45.61, 77.32, 126.56, 128.23, 128.44, 143.63.

1-Phenylpropan-1-ol

Reaction was carried out in a similar manner to the representative procedure using benzaldehyde (106 mg, 1.0 mmol). The title compound was obtained in 90% yield. Quenching the reaction mixture with D_2SO_4 (98% in D_2O) gave 3-deutero-1-phenylpronan-1-ol with 85% D incorporation. The title compound, ^1H NMR ($CDCl_3$, Me_4Si): δ 0.84 (t, J = 7.6 Hz, 3H), 1.6-1.8 (m, 2H), 4.7 (t, J = 6.6 Hz, 1H), 7.20-7.32 (m, 5H). ^{13}C NMR: δ 10.12, 31.78, 75.83, 126.02, 127.32, 128.28, 144.62. 3-deutero-1-phenylpronan-1-ol, ^1H NMR ($CDCl_3$, Me_4Si): δ 0.86-0.94 (m, 2H), 1.6-1.8 (m, 2H), 4.59 (t, J = 7 Hz, 1H), 7.20-7.32 (m, 5H). ^{13}C NMR: δ 9.87 (t, $^1J_{C\text{-}D}$ = 19.6 Hz), 31.81, 76.03, 125.98, 127.49, 128.41, 144.62.

3-Ethylpentan-3-ol

Zirconocene-ethylene complex, $Cp_2Zr(CH_2{=}CH_2)(PPh_2Me)$ **1a**, was prepared in the same way as described above. To the solution of **1a** was added pentan-3-one (86 mg, 1.0 mmol) dropwise via syringe throughout 50 min. After the mixture was stirred for additional 10 min, the yellow solution was added 3 N HCl and extracted with ether. Usual work-up followed by bulb-to-bulb distillation gave title compound (78% yield). Yields were determined by GC. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.86 (t, J = 7.6 Hz, 9H), 1.46 (q, J = 7.6 Hz, 6H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.73, 30.51, 74.73.

Undecan-4-ol

Reaction was carried out in a similar manner to the representative procedure using propylmagnesium chloride (2.0 M diethyl ether solution, 2.0 mmol) instead of ethylmagnesium bromide, and octyl aldehyde (128 mg, 1.0 mmol). The title compound was obtained in Yield 71%. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, J = 7 Hz, 3H), 0.93 (t, J = 7 Hz, 3H), 1.29-1.47 (m, 16H), 3.60 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.06, 14.10, 18.85, 22.67, 25.68, 29.32, 29.71, 31.86, 37.58, 39.74, 71.76.

5-Ethylnonan-4-ol

The title compound was obtained in 46% yield as a 1/1 mixture of diastereomeric isomers. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.86-0.90 (m, 6H), 0.93 (t, J = 7 Hz, 3H), 1.28-1.43 (m, 13H), 3.62 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.09, 14.14, 18.86, 22.69, 25.70, 29.33, 29.72, 31.88, 37.59, 39.75, 71.78.

2-Phenylhexan-3-ol

Reaction was carried out in a similar manner to the representative procedure using propylmagnesium chloride and DL-2-phenylpropionaldehyde (134 mg, 1.0 mmol). The title compound was obtained in 48% yield as a mixture of diastereomeric isomers. For major product, (R,R)/(S,S)-2-Phenylhexan-3-ol. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.86 (t, J = 6.6 Hz, 3H), 1.2-1.5 (m, 4H), 1.28 (d, J = 7 Hz, 3H), 2.65 (dq, J = 7, 7 Hz, 1H), 3.6-3.7 (m, 1H), 7.1-7.4 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.03, 15.62, 19.23, 36.89, 45.72, 75.92, 126.31, 127.82, 128.41,

144.78. For minor product, (R,S)/(S,R)-2-Phenylhexan-3-ol. ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.41, 17.89, 18.96, 36.64, 46.09, 75.80, 126.58, 128.23, 128.46, 143.59.

1-Phenylbutan-1-ol

The title compound was obtained in a similar manner to the representative procedure using propylmagnesium chloride and benzaldehyde (106 mg, 1.0 mmol) in 67% yield. Quenching the reaction mixture with D_2SO_4 (98% in D_2O) gave 3-deutero-1-phenylbutan-1-ol with 94% D incorporation. The title compound, ^1H NMR ($CDCl_3$, Me_4Si): δ 0.92 (t, J = 7 Hz, 3H), 1.28-1.34 (m, 1H), 1.38-1.45 (m, 1H), 1.62-1.71 (m, 1H), 1.73-1.83 (m, 1H), 4.65 (t, J = 7 Hz, 1H), 7.25-7.35 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.96, 19.03, 41.27, 74.43, 125.92, 127.47, 128.42, 144.98. 3-deutero-1-phenylbutan-1-ol, ^{13}C NMR ($CDCl_3$, Me_4Si): δ 13.85, 18.65 (t, $^1J_{C\text{-}D}$ = 19 Hz), 41.10, 74.34, 125.91, 127.42, 128.37, 144.94.

3-Ethylhexan-3-ol

Zirconocene-propylene complex, $Cp_2Zr(CH_2{=}CHCH_3)(PPh_2Me)$, was prepared in the same way as described above. To a solution of the propylene complex was added pentan-3-one (86 mg, 1.0 mmol) dropwise via syringe throughout 50 min. After the mixture was stirred for additional 10 min, the yellow solution was added 3 N HCl and extracted with ether. Usual work-up followed by bulb-to-bulb distillation gave title compound (40% yield). Yields were determined by GC. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.82 (t, J = 7.4 Hz, 6H), 0.89 (t, J = 7 Hz, 3H), 1.42 (q, J = 7.4 Hz, 4H), 1.2-1.4 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.70, 14.70, 16.61, 30.98, 40.61, 74.59.

Dodecan-5-ol

Reaction was carried out in a similar manner to the representative procedure using butyllithium (1.6 M hexane solution, 2.0 mol) instead of ethylmagnesium bromide, and octyl aldehyde (128 mg, 1.0 mmol). The title compound was obtained in 29% yield. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, J = 6.9 Hz, 3H), 0.91 (t, J = 6.9 Hz, 3H), 1.2-1.6 (m, 18H), 3.6-3.8 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.12, 14.12, 22.74, 22.84, 25.75, 27.92, 29.40, 29.77, 31.93, 37.25, 37.55, 72.09.

6-Ethyldecan-5-ol

The title compound was obtained in 64% yield as a ca 1/1 mixture of diastereomeric isomers. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.89-0.93 (m, 9H), 1.18-1.43 (m, 15H), 3.61 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 11.92, 11.99, 14.11, 14.11, 21.70, 21.70, 22.85, 22.85, 23.19, 23.19, 28.42, 28.42, 28.61, 28.61, 29.41, 29.41, 29.82, 29.97, 33.82, 33.82, 45.27, 45.27, 73.51, 73.59.

2-Phenylheptan-3-ol

Reaction was carried out in a similar manner to the representative procedure using butyllithium and DL-2-phenylpropionaldehyde (134 mg, 1.0 mmol). The title compound was obtained in 35% yield as a mixture of diastereomeric isomers. For major product, (R,R)/(S,S)-2-phenylheptan-3-ol. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.86 (t, J = 7 Hz, 3H), 1.2-1.5 (m, 6H), 1.29 (d, J = 6.9 Hz, 3H), 2.7-2.8 (m, 1H); 3.5-3.7 (m, 1H). 7.1-7.4 (m, 5H). ^{13}C NMR: δ: 14.05, 15.49, 22.66, 28.25, 34.41, 45.62, 76.15, 126.29, 127.80, 128.39, 144.78. For minor product, (R,S)/(S,R)-2-

phenylheptan-3-ol. ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.05, 17.93, 22.79, 27.92, 34.16, 46.04, 76.03, 126.17, 128.21, 128.46, 143.57.

Reactions of zirconacyclopentanes with aldehydes

A reaction of 1,1-(η^5-cyclopentadienyl)-3-hexylzirconacyclopentane (2a)

1,1-(η^5-Cyclopentadienyl)-3-hexylzirconacyclopentane **2a** was prepared in situ from Cp_2ZrCl_2, EtMgBr and 1-octene by reported method.[20] To a solution of 2a in THF was added DL-2-phenypropionaldehyde (134 mg, 1.0 mmol) at room temperature. After stirring for 1h, the reaction mixture was quenched with dil.HCl. Usual work-up gave 2-phenylpentan-3-ol as a 2:1 mixture of diastereoisomers (yield 73% by GC).

A reaction of 1,1-(η^5-cyclopentadienyl)zirconacyclopentane (2b)

To a solution of Cp_2ZrCl_2 (292 mg, 1.0 mmol) in THF (5 mL) was added $BrMg(CH_2)_4MgBr$ (1.0 mmol) at -78°C. After stirring for 1h, DL-2-phenylpropionaldehyde (134 mg, 1.0 mmol) was added to the reaction mixture at -10 °C. The reaction mixture was warmed up to room temperature and was stirred for 1h. Quenching with dil.HCl and usual work-up gave 2-phenylpentan-3-ol as a mixture of diastereoisomers (yield 53% by GC).

Preparation of Zirconocene-vinylsilane complexes

Representative Procedure; $Cp_2Zr(CH_2{=}CHSiMe_3)(PMe_3)$ (10a)

To a solution of Cp_2ZrCl_2 (292 mg, 1 mmol) in THF (5 mL) was added butyllithium (1.6 M hexane solution, 2 mmol) at -78 °C. After stirring for 1h at same temperature, trimethylphosphine (1.0 M THF solution, 1.3M) and vinyltrimethylsilane (110 mg, 1.1 mmol) was added and the mixture was allowed to be warmed up to room temperature. The reaction mixture was stirred for 1 h. Observation by ^1H NMR showed formation of title compound (93% yield by ^1H NMR) as a 85:15 mixture of isomers. Major isomer, ^1H NMR (C_6D_6/THF, Me_4Si): δ -0.82 (dd, J = 13.3, 14.2 Hz, 1H), 0.00 (ddd, $^3J_{P\text{-}H}$ = 5.4 Hz, $^2J_{H\text{-}H}$ = 5.4, $^3J_{H\text{-}H}$ = 14.2 Hz, 1H), 0.17 (s, 9H), 0.54 (ddd, $^3J_{P\text{-}H}$ = 10.5 Hz, $^2J_{H\text{-}H}$ = 5.6 Hz, $^3J_{H\text{-}H}$ = 13.3, 1H), 1.15 (d, $^2J_{P\text{-}H}$ = 5.6 Hz, 6H), 5.14 (d, $^3J_{P\text{-}H}$ = 1.7 Hz, 5H), 5.22 (d, $^3J_{P\text{-}H}$ = 1.7 Hz, 5H). ^{13}C NMR (C_6D_6/THF, Me_4Si): δ 2.08, 17.12, 17.39, 21.20, 99.33, 100.95. Minor isomer, ^1H NMR (C_6D_6/THF, Me_4Si): δ 0.10 (s, 9H, $Si(CH_3)_3$), 1.23 (d $^3J_{P\text{-}H}$ = 5.6 Hz, 9H, $P(CH_3)_3$), 5.14 (d, $^3J_{P\text{-}H}$ = 1.7 Hz, 5H, Cp), 5.22 (d, $^3J_{P\text{-}H}$ = 2.0 Hz, 5H, Cp). ^{13}C NMR (C_6D_6/THF, Me_4Si): δ 3.38 ($Si(CH_3)_3$), 18.1 ($P(CH_3)_3$), 100.47 (Cp), 102.08 (Cp).

$Cp_2Zr(CH_2{=}CHSiPh_3)(PMe_3)$ (10b)

Reaction was carried out similarly to the preparation of $Cp_2Zr(CH_2{=}CH(SiMe_3)(PMe_3)$ using vinyltriphenylsilane (315 mg 1.1 mmol). The reaction mixture was stirred for 12h. ^1H NMR spectrum showed formation of title compound (94% yield by ^1H NMR) as a single isomer. ^1H NMR (C_6D_6, Me_4Si): δ 0.08 (dd, J = 13.5, 13.5 Hz, 1H), 0.45 (ddd, $^2J_{H\text{-}H}$ = 6 Hz, $^3J_{H\text{-}H}$ = 13.5 Hz, $J_{P\text{-}H}$ = 6 Hz, 1H), 0.71 (d, $^2J_{P\text{-}H}$ = 5.9 Hz, 9H), 0.87 (ddd, $^2J_{H\text{-}H}$ = 6.1 Hz, $^3J_{H\text{-}H}$ = 13.5 Hz,

$J_{P\text{-}H}$ = 9.4 Hz, 1H), 4.88 (d, $J_{P\text{-}H}$ = 2.0 Hz, 5H), 5.13 (d, $J_{P\text{-}H}$ = 1.7 Hz, 5H), 7.16-7.34 (m, 9H), 8.10-8.14 (m, 6H). ^{13}C NMR (C_6D_6, Me_4Si): δ 8.39 ($J_{C\text{-}P}$ = 2.5 Hz), 16.68 ($J_{C\text{-}P}$ = 18.3 Hz), 22.17 ($J_{C\text{-}P}$ = 14.7 Hz), 99.98, 101.38, 127.65, 128.23, 136.91, 141.24.

Reaction of $Cp_2Zr(CH_2{=}CHSiR_3)(PMe_3)$ (R = Me, Ph) with Ketones

Formation of 2,2-bis(η^5-cyclopentadienyl)-5,5-diethyl-3-trimethylsilyl-1-oxa-2-zirconacyclopentane (11a)

To a solution of Cp_2ZrCl_2 (0.292 g, 1 mmol) in THF (5 mL) was added dropwise hexane solution of butyllithium (1.68 M, 2.0 mmol) at -78 °C. After stirring for 1 h at -78 °C, vinyltrimethylsilane (110 mg, 1.1 mmol) and trimethylphosphine (1.0 M in THF, 1.3 mmol) were added and the reaction mixture warmed to room temperature and stirred for an additional hour. Zirconocene-vinylsilane complex was formed quantitatively in this stage. To the reaction mixture was added pentan-3-one (86 mg, 1.0 mmol) and stirred for 1h. ^{1}H NMR observation showed formation of title compound was observed in 88% yield (by ^{1}H NMR). After removal of volatile, residue was dissolved in benzene and followed by filtration. Filtrate was dried up and oily solid was obtained. Products were characterized by ^{1}H and ^{13}C NMR. ^{1}H NMR (C_6D_6, Me_4Si): δ 0.10 (s, 9H), 0.71 (t, J = 7.6 Hz, 3H), 0.81 (t, J = 7.6 Hz, 3H), 1.3-1.5 (m, 1H), 1.43 (q, J = 7.6 Hz, 2H), 1.6-1.7 (m, 1H), 2.40 (dd, ^2J = 15 Hz, ^3J = 3.3 Hz, 1H), 2.45 (dd, J = 3.3, 15 Hz, 1H), 2.85 (dd, ^2J = 15 Hz, ^3J = 15 Hz, 1H), 5.92 (s, 5H), 6.02 (s, 5H). ^{13}C NMR: δ 1.13, 8.13, 9.16, 28.39, 32.40, 45.12, 52.61, 88.39, 111.43, 112.49.

2,2-Bis(η^5-cyclopentadienyl)-5-ethyl-5-(2-methylpropyl)-3-trimethylsilyl-1-oxa-2-
zirconacyclopentane (11b)

Reaction was carried out in a similar manner to the representative procedure using 5-methylhexan-3-one (114 mg, 1.0 mmol). The title compound was obtained in 71% yield with >95% regioselectivity as a 1:1 mixture of diastereomeric isomers. For *trans*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.10 (s, 9H); 0.82 (t, J = 7.6 Hz, 3H), 0.95 (d, J = 6.5 Hz, 3H), 1.06 (d, J = 6.5 Hz, 3H), 1.3-1.4 (m, 1H), 1.5-1.7 (m, 3H), 2.35-2.55 (m, 2H), 2.75-2.95 (m, 1H), 5.90 (s, 5H), 6.01 (s, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ: 1.35, 9.79, 24.68, 24.76, 24.79, 34.93, 44.75, 46.36, 54.99, 89.33, 111.49, 112.62. For *cis*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.10 (s, 9H); 0.80 (t, J = 7.6 Hz, 3H), 0.97 (d, J = 6.5 Hz, 3H), 0.98 (d, J = 6.5 Hz, 3H), 1.2-1.4 (m, 2H); 1.5-1.7 (m, 2H), 2.35-2.55 (m, 2H), 2.75-2.95 (m, 2H), 5.97 (s, 5H), 6.04 (s, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.30, 9.42, 24.79, 25.47, 25.52, 29.15, 45.82, 48.72, 55.85, 89.55, 111.49, 112.62.

2,2-Bis(η^5-cyclopentadienyl)-5-ethyl-5-methyl-3-trimethylsilyl-1-oxa-2-zirconacyclopentane (11c)

The title compound was obtained in 77% yield with >95% regioselectivity as a 1:1 mixture of diastereomeric isomers. For *trans*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.10 (s, 9H), 0.87 (t, J =7.4 Hz, 3H), 1.15 (s, 3H), 1.2-1.4 (m, 1H), 1.7-1.9 (m, 1H), 2.2-2.5 (m, 1H), 2.5-2.6 (m, 1H), 2.9 (dd; ^2J = 13.5 Hz, ^3J = 13.5 Hz, 1H), 5.91 (s, 5H), 6.02 (s, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ

1.19, 8.90, 26.99, 32.67, 46.09, 54.86, 85.87, 111.39, 112.51. For *cis*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.10 (s, 9H), 0.87 (t, J =7.4 Hz, 3H), 1.07 (s, 3H), 1.4-1.5 (m, 1H), 1.7-1.8 (m, 1H), 2.2-2.5 (m, 1H), 2.4-2.5 (m, 1H), 2.90 (dd; ^2J = 13.5 Hz, ^3J = 13.5 Hz, 1H), 5.93 (s, 5H), 6.01 (s, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.19, 9.29, 24.83, 37.09, 45.64, 54.80, 86.32, 111.46, 112.61.

2,2-Bis(η^5-cyclopentadienyl)-5-methyl-5-phenyl-3-trimethylsilyl-1-oxa-2-zirconacyclopentane (11d)

The title compound was obtained in 87% yield with >97% regioselectivity as a 1.3:1 (*tr*:*cis*) mixture of diastereomeric isomers. For *trans*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.06 (s, 9H), 1.34 (s, 3H); 2.21 (dd, ^3J = 3, 9 Hz, 1H), 3.1-3.3 (m, 2H), 5.80 (s, 5H), 6.07 (s, 5H), 7.1-7.4 (m, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.04, 34.09, 48.70, 54.12, 87.80, 111.53, 112.55, 125.75, 128.04, 128.47, 150.01. For *cis*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.09 (s, 9H), 1.46 (s, 3H), 2.71 (dd, ^3J = 3 Hz, ^3J = 9 Hz, 1H), 2.86 (dd, ^3J = 3 Hz, ^3J = 9 Hz, 1H), 3.1-3.3 (m, 1H), 5.95 (s, 5H), 6.02 (s, 5H), 7.1-7.4 (m, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.24, 30.17, 46.95, 56.13, 86.23, 111.62, 112.77, 124.16, 128.42, 152.82. one carbon overlapped with a solvent signal.

2,2-Bis(η^5-cyclopentadienyl)-5-ethyl-5-phenyl-3-trimethylsilyl-1-oxa-2-zirconacyclopentane (11e)

The title compound was obtained in 83% yield with >98% regioselectivity as a 1:1 mixture of diastereomeric isomers. For *trans*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.02 (s, 9H), 0.61 (t, ^3J = 7.5 Hz, 3H), 1.5-1.7 (m, 2H), 2.15 (dd, ^3J = 4.3 Hz, ^3J = 12.2 Hz, 1H), 3.0-3.2 (m, 2H), 5.79 (s, 5H), 6.06 (s, 5H), 7.1-7.4 (m, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.00, 9.15, 39.00, 48.00, 52.72, 90.74, 111.50, 112.49, 126.59, 127.8, 128.41, 147.62. For *cis*-isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.02 (s, 9H), 0.62 (t, ^3J = 7.3 Hz, 3H), 1.3-1.4 (m, 1H), 2.1-2.3 (m, 1H), 2.65 (dd, ^3J = 3.4 Hz, ^3J = 13.6 Hz, 1H), 2.8 (dd, ^2J = 13.6 Hz, ^3J = 3.4 Hz, 1H), 3.0-3.2 (m, 1H), 5.94 (s, 5H), 5.98 (s, 5H), 7.1-7.4 (m, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.20, 8.07, 34.02, 46.76, 56.15, 88.73, 111.53, 112.61, 124.90, 127.64, 128.41, 150.31.

2,2-Bis(η^5-cyclopentadienyl)-5-cyclopentyl-3-trimethylsilyl-1-oxa-2-zirconacyclopentane (11f)

The title compound was obtained in 85% yield with >97% regioselectivity. ^{1}H NMR (C_6D_6, Me_4Si): δ 0.10 (s, 9H); 1.4-1.8 (m, 8H), 2.46 (dd, ^3J = 3.3 Hz, ^3J = 13.8 Hz, 1H); 2.6 (dd, ^3J = 3.3 Hz, ^2J = 13.5 Hz, 1H), 3.15 (dd, ^2J = 13.5 Hz, ^3J = 14 Hz, 1H), 5.92 (s, 5H), 6.00 (s, 5H). ^{13}C NMR: δ1.28, 24.21, 24.54, 39.84, 40.85, 48.49, 53.99, 95.92, 111.68, 112.57.

Preparation of 11g

Reaction was carried out in a similar manner to the representative procedure using camphor (152 mg, 1.0 mmol). The title compound was obtained in 90% yield with >98% regioselectivity and as a 2:1 mixture of diastereomeric isomers. For major isomer, ^{1}H NMR (C_6D_6, Me_4Si): δ 0.08 (s, 9H), 0.82 (s, 3H), 0.94 (s, 3H), 0.97 (s, 3H); 0.8-0.9 (m, 1H), 1.3-1.4 (m, 2H); 1.5-1.7 (m, 1H); .1.6-1.7 (m, 2H), 2.1-2.2 (m, 1H), 2.25 (dd, ^2J = 13 Hz, ^3J = 3 Hz, 1H), 2.45 (dd, ^3J = 3

Hz, ^3J = 13 Hz, 1H); 3.15 (dd, ^2J = 13 Hz, ^3J = 13 Hz, 1H);5.91 (s, 5H), 6.01 (s, 5H). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.21, 11.92, 20.83, 21.84, 27.41, 30.43, 45.76, 45.76, 46.86, 49.42, 53.26, 54.34, 97.17, 111.67, 112.42. For minor isomer, ^1H NMR (C_6D_6, Me_4Si): δ 5.95 (s, 5H, Cp), 5.99 (s, 5H, Cp). ^{13}C NMR (C_6D_6, Me_4Si): δ 1.55, 14.33, 21.67, 22.20, 27.89, 31.04, 45.86, 50.14, 50.23, 51.72, 53.41, 54.11, 95.72, 110.86, 112.19.

Synthesis of γ-Silylalcohols via Zr-Promoted Coupling Reaction of Trimethylvinylsilane with Ketones

Representative Procedure; 3-Ethyl-1-trimethylsilylpentan-3-ol

To a solution of Cp_2ZrCl_2 (292 mg, 1 mmol) in THF (5 mL) was added dropwise hexane solution of butyllithium (1.68 M, 2 mmol) at -78 °C. After stirring for 1 h at -78 °C, trimethylvinylsilane (110 mg, 1.1 mmol) and trimethylphosphine (1.0 M in THF, 1.3 mmol) were added and the reaction mixture warmed to room temperature and stirred for an additional hour, at which time pentan-3-one (86 mg, 1.0 mmol) was added. After 1 h, the reaction mixture was quenched with 3N HCl, extracted with Et_2O, washed with $NaHCO_3$, brine and dried over $MgSO_4$. Filtration followed by rotavapory concentration provided 141 mg (75% isolated yield) of the title compound with >99% regioisomeric purity. ^1H NMR ($CDCl_3$, Me_4Si): δ -0.03 (s, 9H), 0.35-0.45 (m, 2H), 0.82 (t, J = 7.6 Hz, 6H), 1.2 (bs, 1H), 1.3-1.4 (m, 2H), 1.47 (q, J = 7.6 Hz, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.91, 7.67, 9.54, 30.37, 31.79, 75.04.

3,5-Dimethyl-1-trimethylsilylhexan-3-ol

The title compound was prepared similarly from 4-methyl-2-pentanone (100 mg, 1.0 mmol) in 60% isolated yield and with a >95% regioisomeric purity. ^1H NMR ($CDCl_3$, Me_4Si): δ -0.03 (s, 9H), 0.4-0.45 (m, 2H), 0.93 (d, J = 7.6 Hz, 3H), 0.95 (d, J = 7.6 Hz, 3H), 1.13 (s, 3H), 1.2 (bs, 1H), 1.34 (d, J = 5.9 Hz, 2H), 1.35-1.45 (m, 2H), 1.65-1.68 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.90, 10.13, 24.11, 24.71, 24.89, 26.65, 36.72, 49.58, 73.82.

3-Phenyl-1-trimethylsilylpentan-3-ol

Reaction was carried out in a similar manner to the representative procedure using propiophenone (134 mg, 1 mmol). The title compound was obtained in 68% isolated yield and with a >98% regioisomeric purity. ^1H NMR ($CDCl_3$, Me_4Si): δ -0.04 (s, 9H), 0.20 (ddd, J = 15.0, 15.0, 4.9 Hz, 1H), 0.45 (ddd, J = 15.0, 15.0, 4.9 Hz, 1H), 0.76 (t, J = 7.2 Hz, 3H), 1.65-1.8 (m, 4H), 2.0 (bs, 1H), 7.2-7.55 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.95, 7.83, 9.36, 34.84, 36.30, 77.70, 125.48, 126.09, 127.85, 145.85.

2-Phenyl-4-trimethylsilylbutan-2-ol[19]

The title compound was prepared similarly from acetophenone (120 mg, 1 mmol) in 72% isolated yield and with a > 97% regioisomeric purity. ^1H NMR ($CDCl_3$, Me_4Si): δ -0.04 (s, 9H), 0.2-0.5 (m, 2H), 1.53 (s, 3H), 1.65-1.9 (m, 2H), 2.05 (bs, 1H), 7.15-7.55 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.93, 10.02, 29.54, 38.06, 75.27, 124.88, 126.36, 128.03, 147.81.

3-Methyl-1-trimethylsilylpentan-3-ol

The title compound was obtained in 68% isolated yield and with a >98% regioisomeric purity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ -0.04 (s, 9H), 0.4-0.45 (m, 2H), 0.84 (t, J = 7.2 Hz, 3H), 1.08 (s, 3H), 1.3-1.4 (m, 2H), 1.35 (bs, 1H), 1.48 (q, J = 7.2 Hz, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.95, 8.28, 9.93, 25.78, 33.29, 35.04, 73.29.

1-(2-Trimethylsilylethyl)cyclopentanol

The title compound was obtained in 75% isolated yield and with a >97% regioisomeric purity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ -0.04 (s, 9H), 0.45-0.55 (m, 2H), 1.4 (bs, 1H), 1.45-1.6 (m, 8H), 1.75-1.8 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.92, 10.76, 24.01, 35.25, 39.13, 83.23.

1-(2-Trimethylsylilethyl)borneol

The title compound was obtained similarly from D-camphor (152 mg, 1.0 mmol) in 75% isolated yield and with a >98% isomeric purity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ -0.03 (s, 9H), 0.35-0.65 (m, 2H), 0.82 (s, 3H), 0.83 (s, 3H), 0.85-1.0 (m, 2H), 1.08 (s, 3H), 1.2-1.5 (m, 5H), 1.6-1.7 (m, 2H), 1.87 (dt, J = 13.2, 3.6 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ -1.86, 10.10, 10.84, 20.92, 21.53, 27.08, 30.28, 33.10, 44.96, 45.69, 49.65, 52.09, 81.13.

Reaction of $Cp_2Zr(CH_2{=}CHAr)(PMe_3)$ with diethylketone. Representative procedure; 1-Phenyl-3-ethylpentan-3-ol / 2-phenyl-3-ethylpentan-3-ol

To a solution of Cp_2ZrCl_2 (292 mg, 1.0 mmol) in THF (5 mL) was added dropwise hexane solution of butyllithium (1.68 M, 2 mmol) at -78°C. After stirring for 1 h at -78°C, styrene (114 mg, 1.1 mmol) and trimethylphosphine (1.0 M in THF, 1.2 mmol) were added and the reaction mixture warmed to room temperature and stirred for an additional hour, at which time pentan-3-one (86 mg, 1.0 mmol) was added. After 3 h, the reaction mixture was quenched with 3N HCl, extracted with Et_2O, washed with $NaHCO_3$, brine and dried over $MgSO_4$. Evaporation followed by purification with column chromatography provided the title compounds (84% combined yield). Ratio of two regioisomers was 1-Phenyl-3-ethylpentan-3-ol/2-phenyl-3-ethylpentan-3-ol = 63/37. Yields were determined by gas chromatography. Major product, 1-Phenyl-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.90 (t, J = 7 Hz, 6H), 1.54 (q, J = 7 Hz, 4H), 1.63 (s, 1H, OH), 1.69-1.75 (AA'BB', 2H), 2.59-2.65 (AA'BB', 2H), 7.14-7.35 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.77, 29.85, 30.87, 40.33, 74.52, 125.64, 128.25, 128.34, 142.71. Minor product, 2-phenyl-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.87 (t, J = 7 Hz, 6H), 1.15-1.45 (m, 2H) 1.28 (d, J = 7 Hz, 3H), 1.56 (q, J = 7 Hz, 2H), 2.85 (q, J = 7 Hz, 1H), 7.17-7.31 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.69, 8.01, 15.29, 27.31, 29.09, 45.46 , 75.92 , 126.31, 128.05, 129.20, 143.74.

1-(4-Methylphenyl)-3-ethylpentan-3-ol /2-(4-methylphenyl)-3-ethylpentan-3-ol

The title compounds were prepared similarly from 4-methylstyrene (118 mg, 1.0 mmol) in 79% combined yield. Ratio of two regioisomers was 67/33. Major product, 1-(4-methylphenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.87 (t, J = 8 Hz, 6H), 1.49 (q, J = 8 Hz, 4H), 1.64-1.70 (AA'BB', 2H), 2.28 (s, 3H), 2.52-2.59 (AA'BB', 2H), 7.05 (s, 4H). ^{13}C NMR

($CDCl_3$, Me_4Si): δ 7.85, 20.95, 29.49, 30.93, 40.57, 74.48, 128.21, 129.09, 135.00, 139.75. Minor product, 2-(4-methylphenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.82 (t, J = 7 Hz, 3H), 0.86 (t, J = 8 Hz, 3H), 1.17 (s, 1H, OH), 1.15-1.44 (m, 2H) 1.26 (d, J = 7 Hz, 3H), 1.55 (q, J = 7 Hz, 2H), 2.31 (s, 3H), 2.82 (q, J = 7 Hz, 1H), 7.07-7.17 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.59, 7.89, 15.22, 20.86, 27.14, 28.97, 44.91, 75.74, 128.66, 128.95, 135.65, 140.47.

1-(4-Fluorophenyl)-3-ethylpentan-3-ol / 2-(4-fluorophenyl)-3-ethylpentan-3-ol

The title compounds were obtained in 83% combined yield. Ratio of two regioisomers was 69/31. Major product, 1-(4-fluorophenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.89 (t, J = 7 Hz, 6H), 1.52 (q, J = 7 Hz, 4H), 1.65-1.71 (AA'BB', 2H), 1.79 (s, 1H, OH), 2.56-2.62 (AA'BB', 2H), 6.89-6.97 (m, 2H), 7.09-7.16 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.66, 28.93, 30.73, 40.34, 74.36, 114.91 (d, $|^2J_{C\text{-}F}|$ = 21 Hz), 129.45 (d, $|^3J_{C\text{-}F}|$ = 7 Hz), 138.27 (d, $|^4J_{C\text{-}F}|$ = 4 Hz), 161.02 (d, $|^1J_{C\text{-}F}|$ = 243 Hz). Minor product, 2-(4-fluorophenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.82 (t, J = 7 Hz, 3H), 0.87 (t, J = 7 Hz, 3H), 1.02-1.50 (m, 2H) 1.26 (d, J = 7 Hz, 3H), 1.56 (q, J = 7 Hz, 2H), 2.84 (q, J = 7 Hz, 1H), 6.92-7.01 (m, 2H), 7.18-7.26 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.66, 8.01, 15.54, 27.49, 29.06, 44.76, 75.92, 114.71 (d, $|^2J_{C\text{-}F}|$ = 21 Hz), 130.49 (d, $|^3J_{C\text{-}F}|$ = 7 Hz), 139.50 (d, $|^4J_{C\text{-}F}|$ = 4 Hz), 161.54 (d, $|^1J_{C\text{-}F}|$ = 244 Hz).

1-(4-Chlorophenyl)-3-ethylpentan-3-ol / 2-(4-chlorophenyl)-3-ethylpentan-3-ol

The title compounds were obtained in 63% combined yield. Ratio of two regioisomers was 65/35. Major product, 1-(4-chlorophenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, J = 7 Hz, 6H), 1.51 (q, J = 7 Hz, 4H), 1.63-1.70 (AA'BB', 2H), 2.55-2.61 (AA'BB', 2H), 7.10 (d, 8 Hz, 2H), 7.10 (d, 8 Hz, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.84, 29.25, 30.89, 40.25, 74.46, 128.43, 129.65, 131.34, 141.26. Minor product, 2-(4-chlorophenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.81 (t, J = 8 Hz, 3H), 0.87 (t, J = 8 Hz, 3H), 1.07 (s, 1H, OH), 1.13-1.40 (m, 2H) 1.25 (d, J = 7 Hz, 3H), 1.56 (q, J = 7 Hz, 2H), 2.82 (q, J = 7 Hz, 1H), 7.18-7.26 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.64, 8.00, 15.36, 27.48, 29.06, 44.91, 75.88, 128.07, 130.49, 131.98, 142.35.

1-(4-bromophenyl)-3-ethylpentan-3-ol / 2-(4-bromophenyl)-3-ethylpentan-3-ol

The title compounds were obtained in 63% combined yield. Ratio of two regioisomers was 68/32. Major product, 1-(4-bromophenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, J = 8 Hz, 6H), 1.51 (q, J = 8 Hz, 4H), 1.64-1.70 (AA'BB', 2H), 2.54-2.60 (AA'BB', 2H), 7.03-7.08 (m, 2H), 7.10 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.84, 29.29, 30.87, 40.20, 74.46, 119.33, 130.06, 131.37, 141.74. Minor product, 2-(4-bromophenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.81 (t, J = 8 Hz, 3H), 0.86 (t, J = 8 Hz, 3H), 1.11 (s, 1H, OH), 1.01-1.46 (m, 2H) 1.25 (d, J = 7 Hz, 3H), 1.56 (q, J = 7 Hz, 2H), 2.80 (q, J = 7 Hz, 1H), 7.13-7.17 (m, 2H), 7.38-7.42 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.66, 8.00, 15.33, 27.49, 29.06, 44.98, 75.83, 120.09, 130.91, 131.00, 142.91.

1-(4-methoxyphenyl)-3-ethylpentan-3-ol / 2-(4-methoxyphenyl)-3-ethylpentan-3-ol

The title compounds were obtained similarly from 4-vinylanisole (134 mg, 1.0 mmol) in 84% combined yield. Ratio of two regioisomers was 71/29. Major product, 1-(4-methoxyphenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.88 (t, J = 8 Hz, 6H), 1.50 (q, J = 8 Hz, 4H), 1.64-1.70 (AA'BB', 2H), 2.52-2.58 (AA'BB', 2H), 3.73 (s, 3H), 6.77-6.83 (m, 2H), 7.06-7.11 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.60, 28.72, 30.64, 40.34, 54.90, 74.22, 113.57, 128.91, 134.61, 157.39. Minor product, 2-(4-methoxyphenyl)-3-ethylpentan-3-ol. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.82 (t, J = 7 Hz, 3H), 0.86 (t, J = 8 Hz, 3H), 1.15-1.46 (m, 2H), 1.25 (d, J = 7 Hz, 3H), 1.55 (q, J = 7 Hz, 2H), 2.81 (q, J = 7 Hz, 1H), 3.76 (s, 3H), 6.80-6.85 (m, 2H), 7.14-7.19 (m, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.69, 8.01, 15.45, 27.30, 29.00, 44.56, 55.13, 75.92, 113.42, 130.03, 135.67, 158.09.

1-(2,4,6-trimethylphenyl)-3-ethylpentan-3-ol

The title compound was prepared similarly from 2,4,6-trimethylstyrene (146 mg, 1.0 mmol) in 62% yield and with a >99% regioisomeric purity. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.90 (t, J = 7 Hz, 6H), 1.35 (s, 1H, OH), 1.48-1.58 (m, 6H), 2.22 (s, 3H), 2.28 (s, 6H), 2.56-2.63 (AA'BB', 2H), 6.81 (s, 2H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 7.91, 19.64, 20.77, 23.16, 30.71, 37.63, 74.59, 128.95, 134.84, 135.63, 136.12.

Formation of zirconacyclopentane with $Cp^*_2ZrEt_2$ and styrene

Ethylmagnesium bromide (2 mmol) was added to the suspension of $Cp^*_2ZrCl_2$ (433 mg, 1.0 mmol) in toluene (5 mL) at -78 °C and the mixture was stirred for 1h at room temperature. After adding styrene, the reaction mixture was stirred and warmed up to reflux temperature. To the mixture 3N HCl was added to quench the reaction and usual work-up gave 2-phenylbutane as a single product (yield 38% by GC).

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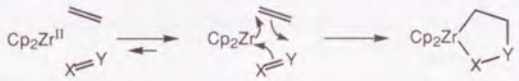
Chapter 6. Zirconium Catalyzed Highly Regioselective Hydrosilation Reaction of Alkenes

Abstract

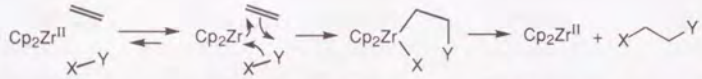
Hydrosilation reaction of alkenes was catalyzed by zirconocene(II) species. The reaction gave the hydrosilation products with the silyl groups at their terminal carbons with excellent regioselectivity. Internal alkenes also afforded terminal silated alkanes involving isomerization of the double bonds. Mechanistic aspects are also discussed.

Introduction

The reactions of zirconocene-alkene complexes with various unsaturated compounds showed selective coupling on zirconium to give zirconacycles as described in previous chapters (eq 6.1). This information prompted the author to investigate possibility of a similar reaction with a single bond. As shown in eq 6.2, coupling of an alkene and X-Y will give acyclic Zr(IV) species and sequent reductive elimination will regenerate Zr(II) accompanied with an addition product. $Cp_2Zr(II)$, in fact, can catalyze hydrogenation of alkenes as shown in chapter 1. In this case H-H can be considered as X-Y in the eq 6.2. It is generally said that the Si-H bond shows similar reactivity to the H-H bond. If hydrosilanes behave as X-Y as described in the equation, an addition reaction of Si-H to alkene will be accomplished.



(6.1)



(6.2)

Hydrosilation reactions catalyzed by late transition metals[1] have been extensively studied. In contrast, few examples have been reported for hydrosilation catalyzed by early transition metals.[2] One possible competing reaction in the latter is polymerization of silanes catalyzed by early transition metals, which can take place even in the presence of alkenes.[3] I describe in this chapter a highly regioselective, zirconium-catalyzed hydrosilation reaction of 1-alkenes, which promises to be of considerable generality and synthetic utility.

$$R^1CH{=}CH_2 \;+\; H_2SiPh_2 \xrightarrow{\text{cat. } Cp_2ZrR'_2} R^1CH_2CH_2SiHPh_2 \qquad (6.3)$$

R^1 = *n*-Hex, *n*-Oct, Ph, etc.; R' = Et or *n*-Bu

Results and Discussion

In the presence of a catalytic amount of the $Cp_2Zr(II)$ species that was prepared from Cp_2ZrCl_2 and EtMgBr or *n*-BuLi, alkenes were treated with hydrosilanes such as H_2SiPh_2 at 25 °C for 1h. Desired hydrosilation products were obtained in good yields with >99% regioselectivity along with $EtSiHPh_2$ (*n*-$BuSiHPh_2$ in the case of *n*-BuLi) obtained in ca.10% yield based on H_2SiPh_2. No dimer of H_2SiPh_2 was detected. The use of just 2 equiv of EtMgBr, i.e., 0.2 mmol, led to only a ca. 10% yield of the hydrosilation products.

The experimental results are summarized in Table 6.1, and the following are noteworthy. First, no reaction is observed with 1-octene and H_2SiPh_2 in the absence of the zirconocene-based

catalyst. The use of Cp_2ZrBu_2 in place of Cp_2ZrEt_2 led to a 75% yield of *n*-$OctSiHPh_2$. Reagents generated in situ by the reaction of Cp_2TiCl_2 and Cp_2NbCl_2 with 2-3 equiv of EtMgBr gave insignificant amounts (<10%) of the desired hydrosilation products. Secondly, not only simple 1-alkene, such as 1-octene and 1-decene, but also styrene and internal alkenes, such as 2-octene and β-methylstyrene, are convertible to the corresponding terminally silated products. Thirdly, the regioselectivity is particularly noteworthy in view of the moderate regioselectivity observed with the previously known catalysts.[1d-f,2c] In the case of internal alkenes, their positional isomerization rather than silane isomerization appears to take place prior to hydrosilation, because cyclic alkenes, such as cyclohexene and cyclooctene, do not give any noticeable amounts of hydrosilation products. Fourthly, the reaction of 1-octene with H_3SiPh catalyzed by 10 mol% of Cp_2ZrEt_2 gave *n*-$OctSiH_2Ph$ in 41% yield, although the corresponding reaction with $HSiEt_3$ did not proceed under the same conditions.

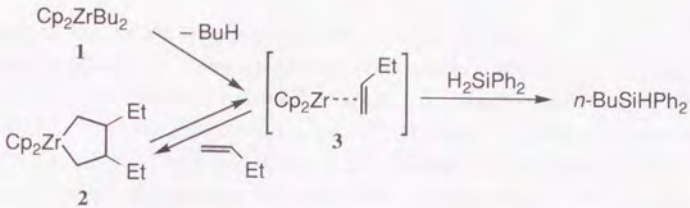
Table 6.1 Hydrosilation of Alkenes Catalyzed by Zirconocene and Related Complexes[a]

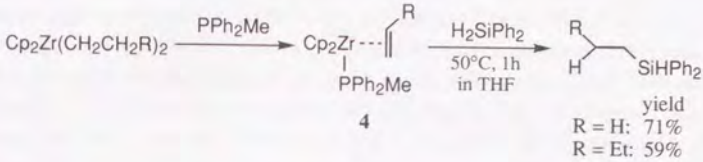
silane	alkene	catalyst	product	yield[b]/%
H_2SiPh_2	1-octene	Cp_2ZrEt_2	*n*-$OctSiHPh_2$	73(65[c])
H_2SiPh_2	1-octene	Cp_2ZrBu_2	*n*-$OctSiHPh_2$	75
H_2SiPh_2	1-octene	Cp_2ZrMe_2	*n*-$OctSiHPh_2$	10
H_2SiPh_2	1-octene	Cp_2TiEt_2	*n*-$OctSiHPh_2$	9
H_2SiPh_2	1-octene	Cp_2NbEt_2	*n*-$OctSiHPh_2$	trace
H_2SiPh_2	2-octene	Cp_2ZrEt_2	*n*-$OctSiHPh_2$	53
H_2SiPh_2	1-decene	Cp_2ZrEt_2	*n*-$DecSiHPh_2$	- (70)
H_2SiPh_2	styrene	Cp_2ZrEt_2	$Ph(CH_2)_2SiHPh_2$	78
H_2SiPh_2	β-methylstyrene	Cp_2ZrEt_2	$Ph(CH_2)_3SiHPh_2$	65
H_3SiPh	1-octene	Cp_2ZrEt_2	*n*-$OctSiH_2Ph$	41

a) The reaction was in THF at 50 °C; alkene/silane/catalyst = 1/1.2/0.1
b) By GLC. c) Isolated yield.

I have so far been mainly concerned with the scope and synthetic potential of the reaction. However, the following results shed some light on its mechanism. The reaction of Cp_2ZrBu_2 with 1 equiv of H_2SiPh_2 gave *n*-$BuSiHPh_2$ in 53% yield. Since it has recently been shown[4] that Cp_2ZrBu_2 **1** decomposes to give Cp_2Zr(1-butene) **3** , it is likely that **3** is an intermediate in the reaction. Even **2**[5] reacted with H_2SiPh_2 to give *n*-$BuSiHPh_2$ in 67% yield, indicating that **2** may serve as a reservoir of **3** (Scheme 6.1). Phosphine stabilized alkene complex **4** which can be isolated at room temperature, in fact, reacted with H_2SiPh_2 to give the hydrosilation product. These results support the mechanism described in eq 6.2.

Scheme 6.1

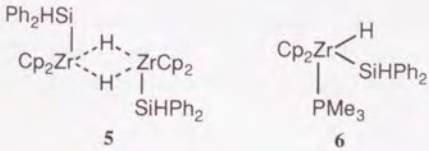




(6.4)

For hydrosilation reaction of alkenes catalyzed by late transition metals, on the other hand, Chalk-Harrod's mechanism have been proposed.[6] In this mechanism, oxidative addition of the Si-H bond to a metal and insertion of alkenes to metal-H or metal-Si bond are suggested. Possibility of this mechanism also cannot be ruled out. The zirconium-catalyzed hydrosilation of 2-octene gave *n*-OctSiHPh$_2$. This result reminds me of a reaction of Schwartz's reagent with internal alkenes that gives terminal zirconated alkanes[7], and implies existence of hydride species.

Co-workers of the author have reported that the reaction of **1** with 2 equiv of H_2SiPh_2 produced not only *n*-BuSiHPh$_2$ but also a yellow crystalline compound **5** in 85% yield. The structure of this complex clearly indicates that some Cp_2Zr(II) derivatives, e.g., **3**, undergo oxidative addition to H_2SiPh_2 to give **5**. This complex, however, was inert to 1-octene, which rules out the intermediacy of **5** in the hydrosilation. In addition, formation of **6** by treatment of **1** with H_2SiPh_2 (2 equiv) and PMe_3 was also reported. When **6** was treated with 1-octene at 60 °C, *n*-OctSiHPh$_2$ was obtained in 80% yield. These results implies that the formation of zirconium(silyl)(hydrido) species.



In the present stage both mechanism are possible and elucidation of these mechanistic details requires further investigation.

Experimental Section

Zirconium Catalyzed Hydrosilation Reaction of Alkenes.

***n*-Octyldiphenylsilane (1): Representative Procedure.** Typically, to a solution of Cp_2ZrCl_2 (292 mg, 0.1 mmol) and THF (5 mL) was added dropwise EtMgBr (1.0 M in THF, 0.3 mmol) at -78 °C. After the mixture was stirred for 1h, H_2SiPh_2 (0.207 mL, 1.1 mmol) and 1-octene (0.156 mL, 1.0 mmol) were sequentially added to, and the mixture was stirred at 25 °C for 1h. The reaction mixture was quenched with 3N HCl, extracted with hexane, washed with $NaHCO_3$, and brine, and dried over $MgSO_4$. Concentration followed by purification by flash chromatography (hexane) provided 0.191 g (65% isol.) of the title compound. Complete consumption of H_2SiPh_2 was observed, and the desired hydrosilation product **1**, was obtained in 73% yield with >99% regioselectivity along with $EtSiHPh_2$ obtained in 10% yield based on H_2SiPh_2. ^1H NMR ($CDCl_3$, Me_4Si): δ 0.86 (t, J = 6 Hz, 3H), 1.0-1.55 (m, 14H), 4.85 (t, J = 3 Hz, 1H), 7.3-7.4 (m, 6H), 7.45-7.6 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 12.13, 14.12, 22.66, 24.39, 29.19, 31.88, 33.19, 127.91, 129.43, 134.69, 135.11. IR (neat) 2120 cm^{-1} (s). High resolution MS calcd for $C_{20}H_{28}Si$: 296.1961, found: 296.1957.

***n*-Decyldiphenylsilane.**[8] ^1H NMR ($CDCl_3$, Me_4Si): δ 0.87 (t, J = 7 Hz, 3H), 1.1-1.5 (m, 18H), 4.84 (t, J = 4 Hz, 1H), 7.3-7.6 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 12.16, 14.13, 22.71, 24.41, 29.23, 29.34, 29.56, 29.64, 31.93, 33.19, 127.96, 129.46, 135.16, 135.71. IR (neat) 2120 cm^{-1}.

***n*-Ethyldiphenylsilane (2).**[9] ^1H NMR ($CDCl_3$, Me_4Si): δ 1.0-1.2 (m, 5H), 4.84 (t, J = 3 Hz, 1H), 7.3-7.4 (m, 6H), 7.5-7.6 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 4.15, 8.14, 127.93, 129.48, 134.41, 135.14. IR (neat) 2120 cm^{-1}.

***n*-Butyldiphenylsilane (3).**[10] ^1H NMR ($CDCl_3$, Me_4Si): δ 0.87 (t, J = 7 Hz, 3H), 1.1-1.15 (m, 2H), 1.35-1.45 (m, 4H), 4.87 (t, J = 4 Hz, 1H), 7.3-7.4 (m, 6H), 7.5-7.6 (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 11.88, 13.72, 26.20, 26.59, 127.92, 129.44, 134.66, 135.11. IR (neat) 2120 cm^{-1}. High resolution MS calcd for $C_{16}H_{20}Si$: 240.1334, found: 240.1329.

Phenethyldiphenylsilane.[11] ^1H NMR ($CDCl_3$, Me_4Si): δ 1.5-1.55 (m, 2H), 2.75-2.8 (m, 2H), 4.89 (t, J = 4 Hz, 1H), 7.1-7.6 (m, 15H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 14.27, 30.44, 125.74, 127.85, 128.07, 128.35, 129.66, 134.09, 135.17, 144.36.

(3-Phenylpropyl)diphenylsilane.[12] ^1H NMR ($CDCl_3$, Me_4Si): δ 1.16 (td, J = 8 and 4 Hz, 2H), 1.75-1.8 (m, 2H), 2.67 (t, J = 8 Hz, 2H), 7.1-7.5 (m, 15H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 11.84, 26.29, 39.22, 125.71, 128.23, 128.52, 129.53, 134.38, 135.13, 142.15.

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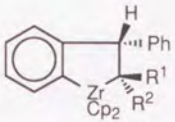
Chapter 7. Zirconium Catalyzed Stereoisomerization of Alkenes

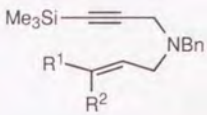
Abstract: Zirconocene-alkene complexes, such as Cp_2Zr(1-butene), can catalyze stereoisomerization of (*Z*)-1,2-disubstituted ethenes. This isomerization reaction is an associative process, which obeys first order in alkenes and second order in zirconocene-alkene complexes which act as catalyst. Mechanistic investigation indicates that the reaction proceeds via a polar path involving benzyl cationic species and zirconate anions.

Introduction

Concerted reaction paths have been implicated in various reactions of zirconocene-alkyne derivatives including benzyne-zirconocenes.[1] Thus, for example, Cp_2ZrPh_2 was reported to reaction with (*E*)- and (*Z*)-stilbenes to give stereospecifically **1a** and **1b**, respectively.[2] Similarly, the Cp_2Zr-promoted bicyclization reaction of **2** proceeds with stereochemical retention to give the corresponding isomers of **3**.[3] On the other hand, the stereochemistry of reactions of zirconocene-alkene derivatives with respect to the *E*-*Z* configuration of the starting alkenes has remained essentially unknown.



1a: R^1=Ph, R^2=H
1b: R^1=H, R^2=Ph



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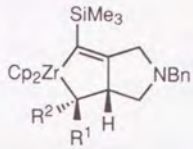
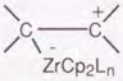


3

a: R^1=Me, R^2=H
b: R^1=H, R^2=Me

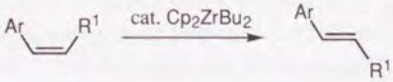
I describe in this chapter that the zirconocene-alkene complexes can also undergo stereoisomerization leading to nonstereospecific but often highly stereoselective processes, which most likely proceeds via novel dipolar zirconate species represented by **4**.



4 (L_n = ligands and Cp_2Zr containing groups)

Results and Discussion

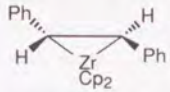
I have found that, in addition to (*Z*)-stilbene,[4] various olefins, such as (*Z*)-PhCH=CHMe and (*Z*)-PhCH=CHSiMe$_3$ undergo stereoisomerization catalyzed by $Cp_2Zr(n\text{-Bu})_2$ (eq 7.1).



(7.1)

A 1:1 mixture of (*Z*)-PhCH=CHPh and (*Z*)-PhCD=CDPh gave a 1:1 mixture of the corresponding *E*-isomers under the influence of $Cp_2Zr(n\text{-Bu})_2$ without a sign of H-D scrambling. Coupled with the fact that there is no allylic hydrogen, two commonly observed transition-metal-mediated stereoisomerization processed, i.e., hydrometalation-dehydrometalation and allylic C-H oxidative addition-reductive elimination,[5] are ruled out.[6] However, isomerization of simple alkyl-substituted alkenes is indeed complicated and even dominated by a more conventional regio- and stereoisomerization process.[5] A detailed NMR study of the isomerization reaction of (*Z*)-stilbene

in the presence of 1 equiv of preformed $Cp_2Zr[(E)$-stilbene] (**5**) has revealed that the stereoisomerization reaction is first order in (*Z*)-stilbene and second order in **5**. Critically important here is that this isomerization proceeds associatively.



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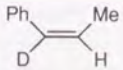

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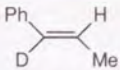

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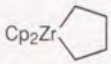

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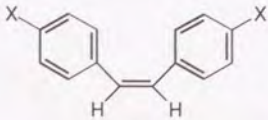
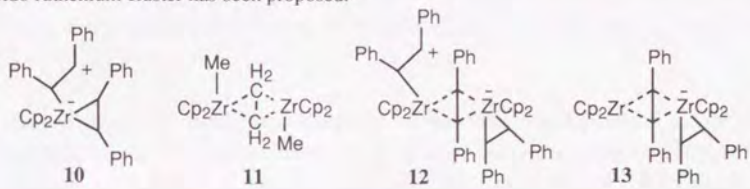


9

a: X = H
b: X = Me
c: X = Cl
d: X = CF_3

In principle, alkene stereoisomerization may involve one or more of C-H and σ and/or π C-C bond cleavages. To rigorously probe this point, we chose (*Z*)-PhCD=CHMe (**6**) as a readily accessible, regio- and stereodefined *Z* olefin containing four different groups around the C=C bond. Its stereoisomerization using 10 mol% of $Cp_2Zr(n\text{-Bu})_2$ produced the *E* isomer **7** without a sign of the formation of any species arising from changes in atom-linking sequences. The results rule out all but the π-bond cleavage mechanisms, for which the homolytic and heterolytic extremes may be considered. Neither Cp_2ZrMe_2 nor zirconacyclopentane **8** in the presence of an excess of ethylene catalyzed *Z*-to-*E* isomerization of stilbene at 23 °C. In fact, no reaction was observed. These results indicate that as such neither dialkylzirconocenes nor zirconacyclopentanes are isomerization catalysts. Since ^{1}H NMR analysis of the isomerization reaction mixtures revealed the presence of Cp_2Zr-alkene complexes, e.g., **5**, as the predominant Cp_2Zr derivatives, they most likely serve as the active catalysts. In order for dialkylzirconocenes and zirconacyclopentanes to act as catalyst precursors, they must therefore be convertible to Cp_2Zr-alkene complexes. To further probe the mode of interaction between an alkene and an Cp_2Zr-alkene, especially the sign and extent of charge buildup on an alkenyl C and Zr, p,p'-disubstituted (*Z*)-stilbenes (>98% *Z*) containing Me, F, Cl, and CF_3 (**9**) were prepared. Isomerization of **9** was carried out in 2:1 THF-C_6D_6 at 23 °C using 10 mol% of $Cp_2Zr(n\text{-Bu})_2$ as the isomerization catalyst, and its progress was monitored by ^{1}H NMR spectroscopy. Under these conditions **9d** remained essentially unchanged over several hours. In the other cases, the signal for the *E* isomer emerged and grew at the expense of those of the *Z* isomer, while those for the Cp_2Zr-(*E*)-stilbene remained essentially constant. No other stilbene-containing or -derived species were detectable. The pseudo-first-order rate constants observed with **9a-c** are 2.94×10^{-4} sec^{-1} (**9a**), 2.57×10^{-4} (**9b**), and 8.93×10^{-6} (**9c**) sec^{-1}. Although a clear-cut linear free energy relationship is not observed, the overall trend in substituent effects seems to points to the involvement of benzyl cationic species. One associative process we initially considered involves **10** as a transient species. However, the second-order rate dependence[7] on

$Cp_2Zr(PhCH{=}CHPh)$ is clearly inconsistent with this view. Our recent elucidation of the structure of $(Cp_2ZrMe)_2(CH_2{=}CH_2)$ (**11**) by NMR and X-ray analyses[8] prompts us to propose **12** as an active species consistent with all of the data presented herein. The modes of Cp_2Zr-alkene interaction and alkene stereoisomerization reflected in **10** and **12** are essentially the same. Significantly, however, dimerization of $Cp_2Zr(PhCH{=}CHPh)$ as depicted in **13** represents a plausible, novel mode of activation of one Zr center as an electrophile by the other. The opportunity for possible, extensive electron delocalization in **12** may also favor the proposed 2:1 interaction. As stereoisomerization mechanism, addition of *Z*-stilbene to metal-metal bond in non-hydrido ruthenium cluster has been proposed.[6]



In summary, the reaction of zirconocene-alkene complexes with alkene can, in some cases, lead to the formation of zirconacyclopentanes via concerted C-Zr bond addition to alkenes, which is thought to involve donation of π-electrons and back-donation of C-Zr bonding electrons. In cases where the back-donation is hindered due to steric and other factors, the alkene-zirconocenes presumably act merely as electron-accepting Lewis acids, leading to the formation of zirconates represented by **4**. This process can be facilitated through dimeric interaction as in **12**. In addition to inducing *E*-*Z* isomerization, **4** could, in some cases, ring-expand to provide zirconacyclopentanes via a polar path as one possibility. These polar processes represent yet another novel reaction pattern that Cp_2Zr derivatives display and show some striking contrasts between alkene-zirconocenes and their alkyne counterparts.

Experimental Section

General. All reactions involving organometallic reagents were carried out under a nitrogen atmosphere. Tetrahydrofuran and hexane were dried over sodium, distilled and kept under nitrogen. Butyllithium (1.6 M hexane solution) and diisobutylaluminum hydride (1.0 M hexane solution) were purchased from Kanto Chemical Co. Inc. Zirconocene dichloride, (*E*)- and (*Z*)-stilbene and other reagents were purchased and used without further purification. p,p'-Disbstitutedstilbenes **9b-e** were prepared by reported method.[9] ^{1}H and ^{13}C NMR spectra were recorded on a JEOL EX-270 FT NMR spectrometer. GC-MS on Shimadzu GCMS-QP1000EX. Deuterium incorporation was determined by ^{13}C NMR (gated decoupling pulse technique without NOE).

Isomerization of Deuterated Stilbenes; Cross-over Experiments. Isomerization reactions of deuterated (*Z*)-stilbenes were carried out in the presence of 10 mol% of Cp_2ZrBu_2 at room temperature for 24 h. To the reaction mixtures were added 3 N HCl. (*E*)-Stilbenes were detected quantitatively by GC and usual work-up followed by purification with column chromatography gave isolated products. Products were characterized by ^{1}H and ^{13}C NMR. Isomerization of an equimolar mixture of (*Z*)-1,2-diphenylethene/(*Z*)-1,2-dideuterio-1,2-diphenylethene gave exclusively (*E*)-1,2-diphenylethene and (*E*)-1,2-dideuterio-1,2-diphenylethene as products. (*E*)-1-Deuterio-1,2-diphenylethene was not detected and less than 5% could present in the isolated mixture judged from S/N ratio of the ^{13}C NMR spectrum. Isomerization of (*Z*)-1-deuterio-1,2-diphenylethene afforded (*E*)-1-deuterio-1,2-diphenylethene as an only product and less than 7% of (*E*)-1,2-diphenylethene or (*E*)-1,2-dideuterio-1,2-diphenylethene could present in the isolated mixture.

Preparation of (Z)-1,2-Dideuterio-1,2-diphenylethene. To a solution of bis(η^5-2,4-cyclopentadien-1-yl)dichlorozirconium (Cp_2ZrCl_2) (1.46 g, 5.0 mmol) in tetrahydrofuran (20 mL) was added butyllithium (1.60 M hexane solution, 10 mmol) at -78 °C and the mixture was stirred for 1h. After adding diphenylacetylene (0.802 g, 4.5 mmol) and methyldiphenylphosphine (1.10 g, 5.5 mmol), the mixture was allowed to be warmed up to room temperature and stirred for 12 h. And then, DCl/D_2O (20 wt%) was added dropwise to the red solution at 0 °C and was stirred overnight at room temperature. The reaction mixture was extracted to ether and organic layer was washed with H_2O, and dried over $MgSO_4$. Purification with column chromatography gave the title compound in 50% of isolated yield. The ^{13}C NMR spectra showed 98% deuterium incorporation. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 7.15-7.26 (m, 10H). ^{13}C NMR ($CDCl_3$, Me_4Si): δ 127.06, 128.17, 128.83, 129.74 (t, $J_{C\text{-}D}$ = 23.5 Hz), 137.11. MS (EI) *m/e* 182 (M^+).

Preparation of (Z)-1-Deuterio-1,2-diphenylethene. To a solution of diphenylacetylene (535 mg, 3.0 mmol) in hexane (2 mL) was added diisobutylaluminum hydride (1.0 M hexane solution, 3.0 mmol) at room temperature. The mixture was warmed up to 50 °C and stirred for 24 h. DCl/D_2O (20wt%) was added dropwise to the reaction mixture at 0 °C.

After extraction to ether, organic layer was washed with H_2O, and dried over $MgSO_4$. Purification with column chromatography gave title compound in 48% isolated yield. The ^{13}C NMR spectra showed 95% deuterium incorporation. ^1H NMR ($CDCl_3$, Me_4Si): δ 6.58 (s, 1H), 7.16-7.26 (m, 10H). ^{13}C NMR($CDCl_3$, Me_4Si): δ 127.04 (two carbons), 128.16 (two carbons), 128.82 (two carbons), 129.85 (t, $J_{C\text{-}D}$ = 24 Hz), 130.06, 137.09, 137.18.

(*E*)-1,2-Dideuterio-1,2-diphenylethene. ^{13}C NMR ($CDCl_3$, Me_4Si): δ 126.45, 127.55, 128.20 (t, $J_{C\text{-}D}$ = 23 Hz), 128.63, 137.18.

(*E*)-1-Deuterio-1,2-diphenylethene. ^1H NMR($CDCl_3$, Me_4Si): δ 7.11 (t, $^3J_{H\text{-}D}$ = 2 Hz, 1H), 7.23-7.29 (m, 2H), 7.33-7.39 (m, 4H), 7.50-7.54 (m, 4H). ^{13}C NMR($CDCl_3$, Me_4Si): δ 126.46, 126.49, 127.57, 127.58, 128.33 (t, $J_{C\text{-}D}$ = 23 Hz), 128.53, 128.65 (two carbons overlapped), 137.20, 137.27.

Isomerization of (*Z*)-Stilbene Using Cp_2Zr((*E*)-stilbene); Determination of Kinetic Order with Respect to Cp_2Zr((*E*)-stilbene). Di-*n*-butylzirconocene was generated as before using Cp_2ZrCl_2 (292 mg, 1.0 mmol) in 5 mL of THF and butyllithium (1.60 M hexane solution, 2.0 mmol). (*E*)-Stilbene (180 mg, 1.0 mmol) and pyrene (101 mg, 0.5 mmol) in THF (2 mL) was added to the mixture of di-*n*-butylzirconocene. The resulting mixture was allowed to warm to room temperature and stirred for 2 h. ^1H NMR showed formation of Cp_2Zr((*E*)-stilbene) (Cp; δ 5.49 ppm) in 47% yield. The solution was concentrated to 4.0 mL. A series of kinetic measurement were carried out using this reaction mixture. Typically, the solution of Cp_2Zr((*E*)-stilbene) (0.17 mL) was transferred to a 5 mmϕ NMR tube. To the solution was added THF (0.13 mL), C_6D_6 (0.3 mL) and (*Z*)-stilbene (3.7 mg, 0.021 mmol). This mixture was monitored by ^1H NMR, in which a probe was regulated to 20 °C. Decrease of a signal for methine protons of (*Z*)-stilbene (δ 6.53 ppm) was observed to determine the rate constants for isomerization reaction. The measurements were carried out in four different concentration of Cp_2Zr((*E*)-stilbene). Concentrations of Cp_2Zr((*E*)-stilbene) were constant during reactions, and the isomerization apparently obeyed the first order rule.
According to an equation

$$-\frac{d[(Z)\text{-stilbene}]}{dt} = k[(Z)\text{-stilbene}][Cp_2Zr((E)\text{-stilbene})]^n,$$

the value $k[Cp_2Zr((E)\text{-stilbene})]^n$ were (1.38±0.06) x 10^{-3}, (4.8±0.2) x 10^{-4}, (3.7±0.1) x 10^{-4} and (1.75±0.05) x 10^{-4} sec^{-1} when concentration of Cp_2Zr((*E*)-stilbene) were 0.059, 0.034, 0.029 and 0.020 $mol{\cdot}L^{-1}$ respectively. Application of least square method for equation

$$\log(k[Cp_2Zr((E)\text{-stilbene})]) = n \log([Cp_2Zr((E)\text{-stilbene})]) + \log k$$

gave n as n = 1.88±0.01 with R^2 = 0.9999, σ_y = 0.0022. Assuming n = 1, 2 and 3, standard deviations for $\log(k[Cp_2Zr((E)\text{-stilbene})])$ were σ_y = 0.1503, 0.0207 and 0.1913 respectively.

Isomerization of (*Z*)-(2-Phenylethenyl)trimethylsilane Using $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$; Determination of Kinetic Order with Respect to $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$. Di-*n*-butylzirconocene was generated as before using Cp_2ZrCl_2 (292 mg, 1.0 mmol) in 5 mL of THF and butyllithium (1.60 M hexane solution, 2.0 mmol). (*E*)-(2-Phenylethenyl)trimethylsilane (177 mg, 1.0 mmol) was added to the mixture of di-*n*-butylzirconocene. The resulting mixture was allowed to warm to room temperature and stirred for 3 h. ^{1}H NMR showed formation of $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$ (Cp; δ 5.31, 5.77 ppm) in 60% yield. The solution was concentrated to ca. 3 mL. A series of kinetic measurement was carried out using this reaction mixture. Typically, the solution of $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$ (0.18 mL) was transferred to a 5 mmϕ NMR tube. To the solution was added THF (0.12 mL), C_6D_6 (0.3 mL), (*Z*)-(2-phenylethenyl)trimethylsilane (17.4 mg, 0.099 mmol) and pyrene (15.2 mg, 0.0752 mmol). Integration of Cp signals relative to those of pyrene indicated concentration of $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$ was 0.0584 mol·L^{-1}. This mixture was monitored by ^{1}H NMR, in which a probe was regulated to 20 °C. Decrease of a signal for trimethylsilyl protons of (*Z*)-(2-phenylethenyl)trimethylsilane (δ 0.05 ppm) was observed to determine the rate constants for isomerization reaction. The measurements were carried out in four different concentration of $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$. Concentrations of $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$ were constant during reactions, and the isomerization apparently obeyed the first order rule.
According to an equation

$$-\frac{d[(Z)\text{-}Me_3SiCH{=}CHPh]}{dt} = k[(Z)\text{-}Me_3SiCH{=}CHPh][Cp_2Zr((E)\text{-}Me_3SiCH{=}CHPh)]^n,$$

the rate constants of isomerization of a title compound were (1.7±0.2) x 10^{-3}, (3.1±0.3) x 10^{-4}, (4.7±0.3) x 10^{-5} and (4.7±0.4) x 10^{-5} sec^{-1} when concentration of $Cp_2Zr((E)$-$Me_3SiCH{=}CHPh)$ were 0.138, 0.0584, 0.0233 and 0.0148 mol·L^{-1}, respectively.
Application of least square method for equation

$$\log(k[Cp_2Zr((E)\text{-}Me_3SiCH{=}CHPh)]) = n\log([Cp_2Zr((E)\text{-}Me_3SiCH{=}CHPh)]) + \log k$$

gave n as $n = 1.7\pm0.2$ with $R^2 = 0.9634$, $\sigma_y = 0.1241$. Assuming n = 1, 2 and 3, standard deviations for $\log(k[Cp_2Zr((E)\text{-}Me_3SiCH{=}CHPh)])$ were $\sigma_y = 0.2910$, 0.1655 and 0.4981 respectively.

Preparation of (*Z*)-(2-Phenylethenyl)trimethylsilane.[10] 1-Trimethylsilyl-2-phenylacetylene was prepared from 1-lithio-2-phenylacetylene and trimethylsilylchloride. To a solution of Cp_2ZrCl_2 (0.876 g, 3.0 mmol) in tetrahydrofuran (15.0 ml) was added butyllithium (1.60 M hexane solution, 6.0 mmol) at -78 °C and the mixture was stirred for 1h. After adding 1-trimethylsilyl-2-phenylacetylene (502 mg, 2.7 mmol) and methyldiphenylphosphine (0.661 mg, 3.3 mmol), the reaction mixture was allowed to be warmed up to room temperature and stirred for 24 h. After adding 3 N HCl, the reaction mixture was extracted to ether. Organic layer was washed with H_2O, and dried over $MgSO_4$. Column chromatography gave title compound in 62%

of isolated yield. ^{1}H NMR ($CDCl_3$, Me_4Si): δ 0.05 (s, 9H), 5.83 (d, 1H, J = 16 Hz), 7.20-7.31 (m, 5H), 7.36 (d, 1H, J = 16 Hz) ^{13}C NMR ($CDCl_3$, Me_4Si): δ 0.16, 127.29, 127.88, 128.10, 132.83, 140.11, 146.59.

(*E*)-1-(2-phenylethenyl)trimethylsilane.[11] ^{1}H NMR($CDCl_3$, Me_4Si): δ 0.16 (s, 9H), 6.48 (d, J = 19 Hz, 1H), 6.87 (d, J = 19 Hz), 7.21-7.35 (m, 3H), 7.42-7.45 (m, 2H). ^{13}C NMR($CDCl_3$, Me_4Si): δ -1.24, 126.34, 127.92, 128.50, 129.50, 138.34, 143.57.

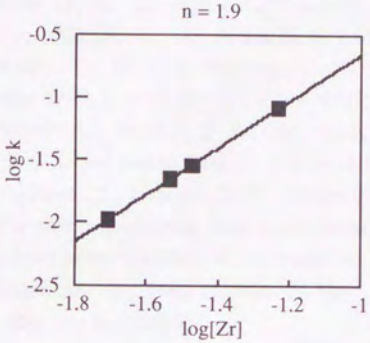
Stereoisomerization of (Z)-Stilbene Catalyzed by Cp_2ZrBu_2. Typically, to a solution of Cp_2ZrCl_2 (292 mg, 1.0 mmol) in THF (7.2 mL) was added butyllithium (2.5 M in hexane solution, 0.8 mL) at -78 °C and was stirred for 1 h. A portion of the reaction mixture (0.4 mL containing 0.05 mmol of Zr) was transferred to a 5 mmϕ NMR tube which contains (*Z*)-stilbene (44.6 mg, 0.25 mmol) and pyrene (22.4 mg, 0.1 mmol) as an internal standard in 0.4 mL of C_6D_6 solution. Concentration of zirconium species in the solution was 0.063 mol·L^{-1}. The sample was observed with ^{1}H NMR at 22 °C and decrease of methine signal of (*Z*)-stilbene at 6.53 ppm was and increase of signals due to *o*-hydrogens of phenyl groups of (*E*)-stilbene at 7.48 ppm were observed to determine the rate constant of isomerization of (*Z*)-stilbene to (*E*)-stilbene. This isomerization reaction displayed apparently first order kinetics and the first order rate constant (= $k[Zr]^n$) was 2.94 x 10^{-4} sec^{-1}.

Stereoisomerization of (Z)-1,2-Bis(4-methylphenyl)ethene Catalyzed by Cp_2ZrBu_2. Isomerization of (*Z*)-1,2-Bis(4-methylphenyl)ethene in the presence of catalytic amount of Cp_2ZrBu_2 was carried out in a similar manner to the representative procedure. The rate was determined by observation of a methine signal of (*Z*)-1,2-bis(4-methylphenyl)ethene at 6.49 ppm and o-hydrogens of (*E*)-isomer at 7.35 ppm. The pseudo-first order rate constant (= $k[Zr]^n$) was 2.57 x 10^{-4} sec^{-1}.

Stereoisomerization of (Z)-1,2-Bis(4-chlorophenyl)ethene Catalyzed by Cp_2ZrBu_2. Isomerization of (*Z*)-1,2-Bis(4-chlorophenyl)ethene in the presence of catalytic amount of Cp_2ZrBu_2 was carried out in a similar manner to the representative procedure. The rate was determined by observation of a methine signal of (*Z*)-1,2-bis(4-chlorophenyl)ethene at 6.38 ppm and o-hydrogens of (*E*)-isomer at 7.23 ppm. The pseudo-first order rate constant (= $k[Zr]^n$) was 8.93 x 10^{-6} sec^{-1}.

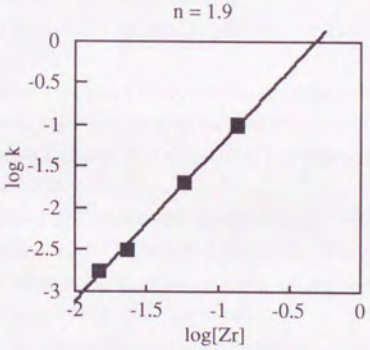
Zirconium Catalyzed Isomerization of (Z)-stilbene in the presence or absence of Additional LiCl. Isomerization of (*Z*)-stilbene was carried out in a similar manner to described above with a solution of (*Z*)-stilbene (0.83 mol·L^{-1}) and 0.1 equiv of Cp_2ZrBu_2. Lithium chloride (4 equiv to Zr) was dissolved in THF solution in advance. The sample was observed with ^{1}H NMR at 20 °C. This isomerization reaction displayed apparently first order kinetics and the first order rate constant (= $k[Zr]^n$) was (2.23±0.08) x 10^{-4} sec^{-1} and (2.38±0.13) x 10^{-4} sec^{-1} in the absence and the presence of additional LiCl, respectively.

Isomerization of (Z)-stilbene:
Determination of n for [Zr]



f(x) = 1.8798*x + 1.2291
R^2 = 9.9995E-1

Isomerization of (Z)-PhC=CSiMe$_3$:
Determination of n for [Zr]



f(x) = 1.861*x + 0.5958
R^2 = 9.968E-1

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2 Kropp, K.; Erker, G. *Organometallics* **1982**, *1*, 1246. See however, Erker, G.; Rosenfeldt, F. *J. Organomet. Chem.* **1982**, *224*, 29.

3 Negishi, E.; Swanson, D. R.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1987**, *28*, 917. See also McDate, C.; Bercaw, J. E. *J. Organomet. Chem.* **1985**, *279*, 281.

4 Takahashi, T.; Swanson, D. R.; Negishi, E. *Chem. Lett.* **1987**, 623.

5 For papers presenting such mechanisms for a different Ti- or Zr- catalyzed alkene isomerization reaction, see: (a) Akita, M.; Yasuda, H.; Nagasaka, K.; Nakamura, A. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 554. (b) Maye, J. P.; Negishi, E. *Tetrahedron Lett.* **1993**, *34*, 3359. see also chapter 5.

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7 The apparent second-order dependence on Cp_2Zr(stilbene) may be due to LiCl generated as a byproduct in the reaction of Cp_2ZrCl_2 with *n*-BuLi. However, addition of LiCl (4 equiv) did not affect the rate of reaction.

8 Takahashi, T.; Kasai, K.; Suzuki, N.; Nakajima, K.; Negishi, E. *Organometallics*, **1994**, *13*, 3413-3414.

9 **9b-e** were prepared by partial reduction of the corresponding 1,2-diarylacetylenes which, in turn, were prepared by the $Pd(PPh_3)_4$-catalyzed reaction of $(\text{-ZnCC-})_n$ with aryl iodide (2 equiv). King, A. O.; Negishi, E.; Villani, F. J., Jr.; Silveira, A., Jr. *J. Org. Chem.* **1978**, *43*, 358.

10 (*E*)-(2-phenylethenyl)trimethylsilane. For ^{1}H NMR data, a) Ennis, D. S.; Gilchrist, T. L. *Tetrahedron* **1990**, *46*, 2623-2632. For ^{13}C NMR, b) Glukhikh, V. I.; Yarosh, O. G.; Glukhikh, N. G.; Pensionerova, G. A.; Voronkov, M. G. *Dokl. Akad. Nauk SSSR (Phys. Chem.)* **1979**, *247*, 1405-1407.

11 (*E*)-(2-phenylethenyl)trimethylsilane. For ^{1}H NMR data, a) Ennis, D. S.; Gilchrist, T. L. *Tetrahedron* **1990**, *46*, 2623-2632. For ^{13}C NMR, b) Glukhikh, V. I.; Yarosh, O. G.; Glukhikh, N. G.; Pensionerova, G. A.; Voronkov, M. G. *Dokl. Akad. Nauk SSSR (Phys. Chem.)* **1979**, *247*, 1405-1407.

Chapter 8. Summary

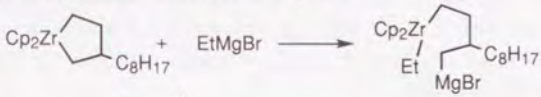
Total Conclusion

In previous chapters 1 to 7, zirconium chemistry was discussed focusing mainly on C-C bond formation. In this chapter, as conclusion, the author would like to summarize these results and give some consideration to property of zirconium complexes and vision of development of catalytic C-C bond formation.

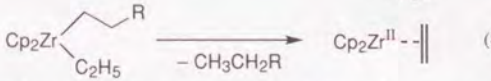
As discussed in chapter 1, two-electron oxidation-reduction process would be important to construct a catalytic cycle. Using zirconocene complexes, Zr^{II} species and Zr^{IV} will play each role and a key C-C bond forming reaction should be oxidative coupling (eq 8.1) rather than reductive elimination because of difficulty of reductive elimination of Cp_2ZrRR'. This is a contrast to the chemistry of late transition metal in which C-C bond formation via reductive elimination is often observed.

(8.1)

Investigation in chapter 2 implied that transmetalation (eq 8.2) with organomagnesium compounds and β-hydrogen elimination (eq 8.3) also important to regenerate Zr^{II} species from zirconacyclopentanes. In addition, high selectivity in these reactions were required to obtain the products in good yields with high selectivity. Participation of resultant ethylene in the next catalytic step is also peculiar in zirconocene compounds.



(8.2)

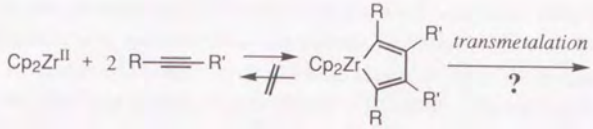


(8.3)

Catalytic allylation described in chapter 3 indicated a new aspects in zirconacycle compounds. Elimination of the β-alkoxy group from a stem of zirconacycle and simultaneous introduction of a double bond (eq 8.4) made it possible to develop various novel carbozirconation reactions of alkynes shown in chapter 4. These tendency can be explained with the oxophilicity

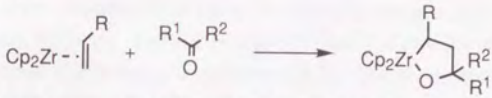
(8.4)

of zirconium metal. There still remain, however, a puzzle that γ-halogen elimination was preferred to that of alkoxy groups in the cyclopropane formation reactions. Although the carbozirconation reactions of alkynes are carried in a stoichiometric manner so far, future investigation may achieve the catalytic reactions. A present major problem to construct catalytic cycles of these reactions are formation of zirconacyclopentadienes via dimerization of alkynes and its low reactivity toward transmetalation and β-β' C-C bond activation (eq 8.5). The solution of this question will give a light on development of novel catalytic C-C bond formation.



(8.5)

It was also possible for zirconocene (II) species to couple carbonyl compounds with alkenes as shown in chapter 5 (eq 8.6). This reaction is also stoichiometric, and to pursue the possibility of transmetalation and/or β- (or γ-) elimination of oxazirconacyclopentanes may achieve the catalytic reaction.



(8.6)

Zirconocene(II) species could catalyze other reactions such as hydrosilation of alkenes (chapter 6) and stereoisomerization of alkenes (chapter 7). The mechanisms of these catalytic reactions are still vague and further investigation will provide more valuable information that will help us to expand the area of these chemistry.

Finally, the author would like to close my thesis with some words that zirconocene chemistry has very attractive aspects which you will not observe in late transition metal chemistry. Application of these early transition metals not only as Lewis acid but also as 'transition metals' will be one of the most interesting and valuable subject. It would expand a new area of organometallic chemistry.

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Noriyuki Suzuki

Nori Suzuki

Coordination Chemistry Laboratories,
Institute for Molecular Science
1995 March

List of Publications

Chapter 2. Mechanistic Consideration on Zirconium Catalyzed Alkene-Alkene Coupling Reaction: Basic Patterns

1. "Catalytic Hydrogenation of Alkenes Using Zirconocene-Alkene Complexes"
   Takahashi, T.; Suzuki, N.; Kageyama, M.; Nitto, Y.; Saburi, M.; Negishi, E.-i.
   Chem. Lett., **1991**, 1579-1582.

2. "Novel Head-to-Tail Alkyl-Alkene Coupling via Zirconium Catalyzed Reactions of Alkylmagnesium Derivatives with Monosubstituted Alkenes"
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3. "Mechanistic Aspects for Zirconium Catalyzed Highly Regioselective Carbon-Carbon Bond Formation Reactions"
   Takahashi, T.; Suzuki, N.; Seki, T.; Nitto, Y.; Saburi, M.; Rousset, C. J.; Choueiry, D.; Negishi, E.-i.
   J. Am. Chem. Soc., submitted.

Chapter 3. Zirconium Catalyzed Novel Allylation Reactions

4. "Zirconium Catalyzed Highly Regioselective Carbon-Carbon Bond Formation Reactions"
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5. "Zirconium Catalyzed or Mediated Regioselective C-C Bond Formation Reactions of Allylic Acetals"
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6. "A Novel Type of Zirconium-Catalyzed or -Promoted Cyclization Reaction"
   Takahashi, T.; Kondakov, D. Y.; Suzuki, N.
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Chapter 4. Novel Type of Carbozirconation Reactions of Alkynes

7. "Allylzirconation of Alkynes by the Reactions of Zirconocene-Alkyne Complexes with Allylic Ethers"
   Takahashi, T.; Suzuki, N.; Kageyama, M.; Kondakov, D. Y.; Hara, R.
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    Suzuki, N.; Kondakov, D. Y.; Kageyama, M.; Kotora, M.; Hara, R.; Takahashi, T.
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Chapter 5. Coupling of Alkenes with Ketones or Aldehydes on Zirconium

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Chapter 6. Zirconium Catalyzed Highly Regioselective Hydrosilation Reaction of Alkenes

13. "Zirconium-Catalyzed Highly Regioselective Hydrosilation Reaction of Alkenes and X-ray Structures of Silyl(hydrido)zirconocene Derivatives"
Takahashi, T.; Hasegawa, M.; Suzuki, N.; Saburi, M.; Rousset, C. J.; Negishi, E.-i.
J. Am. Chem. Soc., **1991**, *113*, 8564-8566.

Chapter 7. Zirconium Catalyzed Stereoisomerization of Alkenes

See ref 15.

In addition, the author also contributed following papers.

14. "Factors Affecting the Unusual Reactivity Order in the β-Hydrogen Abstraction of Dialkylzirconocenes"
Negishi, E.-i.; Nguyen, T.; Maye, J. P.; Choueiri, D.; Swanson, D. R.; Suzuki, N.; Takahashi, T.
Chem. Lett., **1992**, 2367-2370.

15. "Nonconcerted Paths for Reactions of Alkene-Zirconocene Complexes"
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16. "Titanium and Zirconium Chemistry. IV. Polymerization of Epoxides Catalyzed by Early Transition Metal Compounds: Role of Catalyst Ligands"
Suzuki, N.; Miyama, Y.; Takahashi, T.; Noguchi, H.; Saburi, M.; Uchida, Y.
J. Polym. Sci. Part A: Polym. Chem., **1992**, *30*, 2067-2069.

17. "Monohalogenation of Zirconacyclopentane Complexes via Alkylalkoxyzirconocene"
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Takahashi, T.; Xi, Z.; Rousset, C. J.; Suzuki, N.
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19. "Highly Chemoselective Reactions of Zirconacyclopentenes for Selective Functionalization"
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23. "Isolation and Characterization of $(Cp_2ZrMe)_2(CH_2CH_2)$"
Takahashi, T.; Kasai, K.; Suzuki, N.; Nakajima, K.; Negishi, E.-i.
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24. "Novel Syntheses of Eight-Membered-Five-Membered Fused-Ring Compounds from Zirconacyclopentadienes"
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25. "Chemoselective C-C Bond Formation Reaction of Zirconacyclopentenes"
Kasai, K.; Kotora, M.; Suzuki, N.; Takahashi, T.
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26. "Intramolecular Coupling of Alkynyl Groups of Bis(alkynyl)silane Mediated by Zirconocene Compounds: Formation of Silacyclobutene Derivatives"
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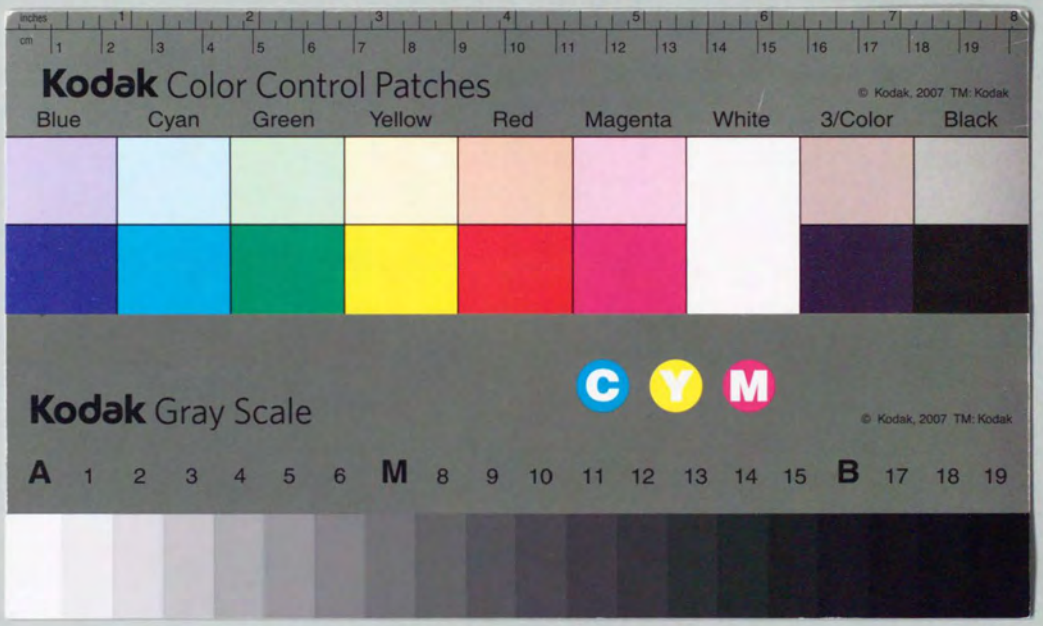
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