Development of Novel Tandem Reactions via Ring-Opening of Cyclopropenes

博士論文

シクロプロペンの開環を鍵とした新規タンデム反応の開発

Development of Novel Tandem Reactions via Ring-Opening of Cyclopropenes

金沢大学大学院自然科学研究科

物質科学専攻

学籍番号：1223132005

氏　　名：中野 健央

主任指導教員名：宇梶　裕

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Takeo Nakano

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Contents

Introduction

I. C-C Bond Activation

C–C bond activation is the powerful approach to the design of novel selective and efficient synthesis of structurally complex molecules in single operation. Therefore, many groups have developed the methods of C–C bond activation using metal complex. However, in previous reports, the expensive transition metal catalyst or high temperature was required to realize the activation of C–C bond. Furthermore, the selectivity of C–C bond cleavage is difficult to control. From these views, the development of the more efficient method of C–C bond activation is a challenging task.

I-a. C-C Bond Activation Using Metal Complex

The C–C bond activation has been achieved with the insertion of metal complex by the strained molecule-metal orbital interaction. For instance, oxidative addition of metal catalyst allows the C–C bond activation of cyclopropanes (Figure 1).[1] The bent bond of cyclopropane increased the interaction with metal orbital. Namely, cyclopropane HOMO and LUMO allow the interaction with metal LUMO (p_y) and HOMO (d_{xy}) to promote the oxidative addition. This method has been widely used for C–C bond activation of strained systems, such as cyclopropane and cyclobutane in the presence of transition metal catalyst, such as Pt, Rh, Ru, Pd and Ir.[1,2] Concretely, in 1971, McQullian and Powell reported the insertion of Pt complex into C–C bonds of cyclopropanes (Scheme 1).[3]

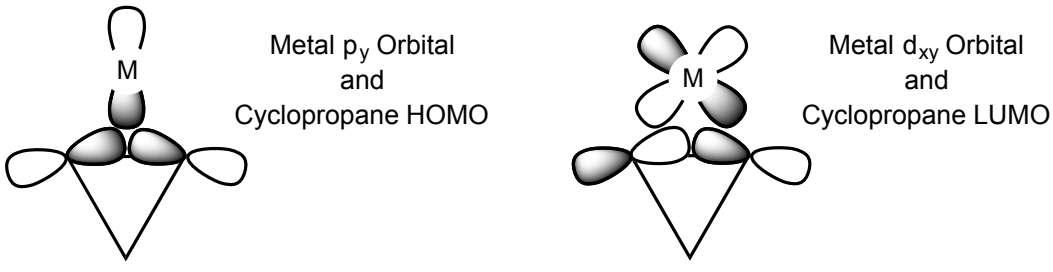
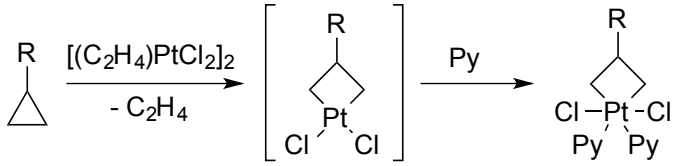


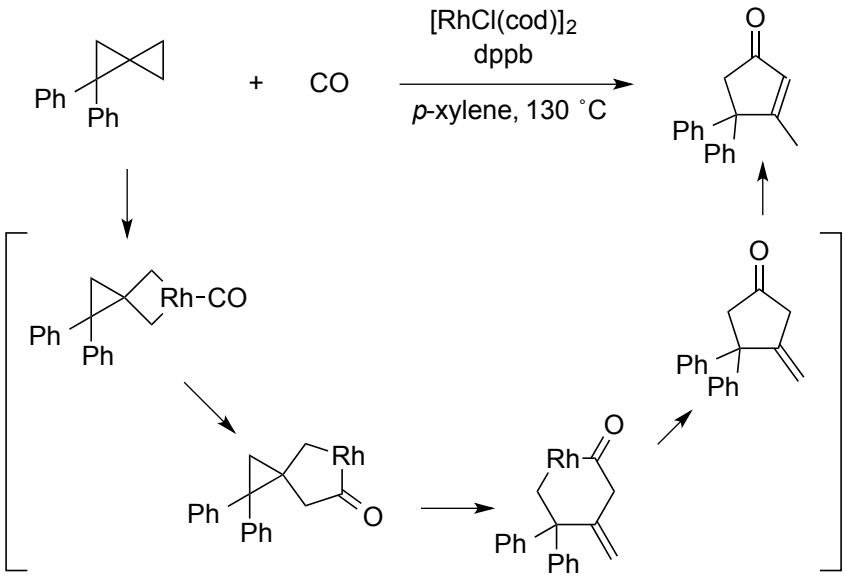
Figure 1. Orbital interaction between cyclopropane and metal

Scheme 1. Insertion of Pt Complex into Cyclopropanes



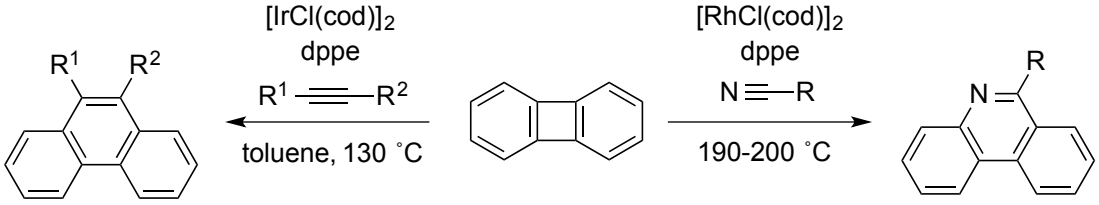
In 2007, Murakami and co-workers reported the Rh-catalyzed carbonylation reaction of spiropentane involving two different types of C–C bond cleavage processes; oxidative addition and b-carbon elimination. This reaction afforded the cyclopentenone (Scheme 2).[4]

Scheme 2. Carbonylation of Spiropentane via C–C Bond Cleavage Sequence



In 2012, Kotora and co-workers reported the catalytic cleavage of the C–C bond in strained aromatic systems (Scheme 3).[5] In this report, the cleavage of biphenylene with Ir or Rh catalyst and subsequent reaction with alkynes or nitriles gave the polycyclic aromatic compounds.

Scheme 3. C–C Bond Activation of Biphenylene



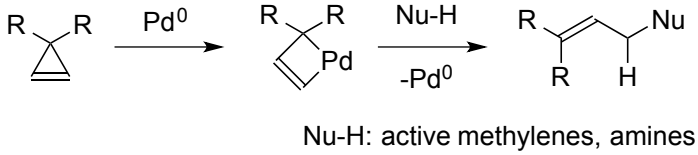
I-b. Ring-Opening Reaction of Cyclopropenes

Cyclopropenes show the unique reactivity due to the highly strained system.[6] Moreover, the cyclopropenes are readily accessible organic molecules. Therefore, they are widely used in organic synthesis.

I-b-1. Ring-Opening of Cyclopropenes Using Transiton Metal Catalysts

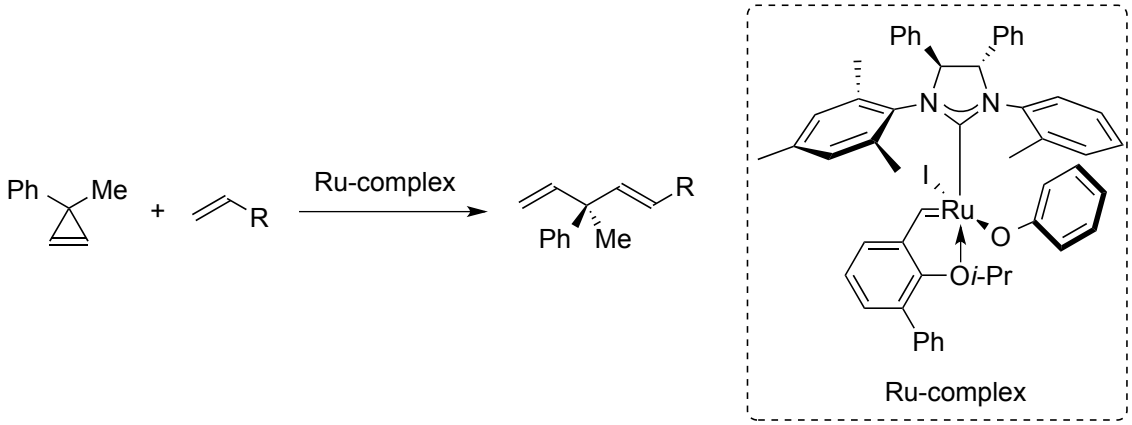
In 2003, the reation of 3,3-dialkylcyclopropene with carbon and amine nucleophile in the presence of Pd catalysts was reported by Yamamoto and co-workers (Scheme 4).[7] This reaction involves the oxidative insertion of Pd catalyst into cyclopropene to give the allylated nucleophile.

Scheme 4. Pd-Catalyzed Ring-Opening Reaction of Cyclopropenes



Furthermore, ring-opening of cyclopropenes were reported by Hoveyda group in 2007 (Scheme 5).[8] The Ru-catalyzed ring-opening/cross-metathesis gave the diene products in high enantioselectivity.

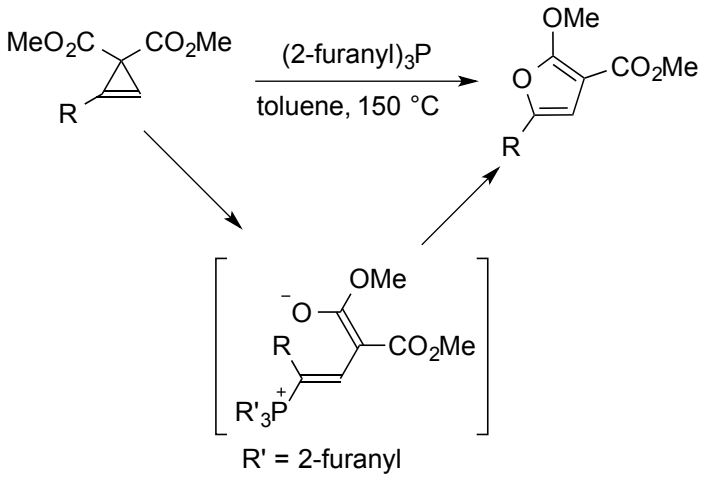
Scheme 5. Ring-Opening of Cyclopropene via Cross-Metathesis



I-b-2. Ring-Opening of Electronically Activated Cyclopropenes

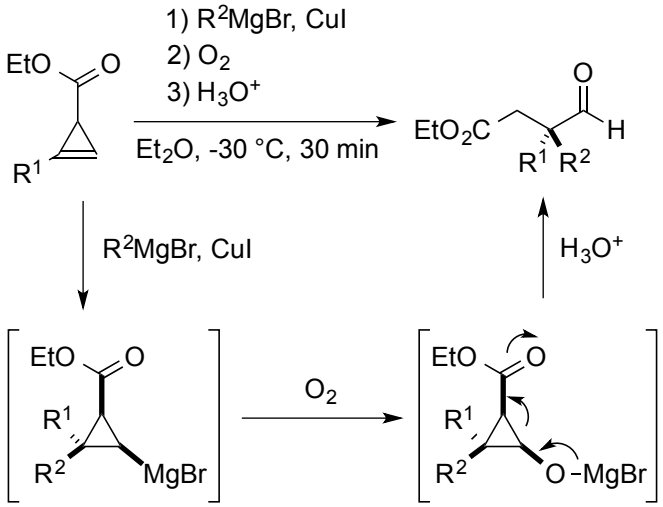
The C–C bond activation is usually required to use the transition metal catalyst. However, the use of these transition metal catalysts could be problems in terms of the high cost, pollution of the environment, and the exhaustion of rare earth elements. On the other hand, activation of the cyclopropenes by electron withdrawing group promoted the ring-opening reaction without expensive transition metal catalyst. In 2011, Ma and co-workers developed nucleophilic addition to electronically activated cyclopropenes to give the furan derivatives.[9] This reaction proceeded via ring-opening cycloisomerization by phosphine catalyst (Scheme 6).

Scheme 6. Phosphine Catalyzed Ring-Opening Cycloisomerization



In 2013, Marek and co-workers developed Cu-catalyzed carbometalation of cycloprpenes, oxidation, and retro aldol-type C-C bond cleavage sequence (Scheme 7).[10] This reaction allows the aldehydes bearing a-quaternary stereocenters in one-pot reaction.

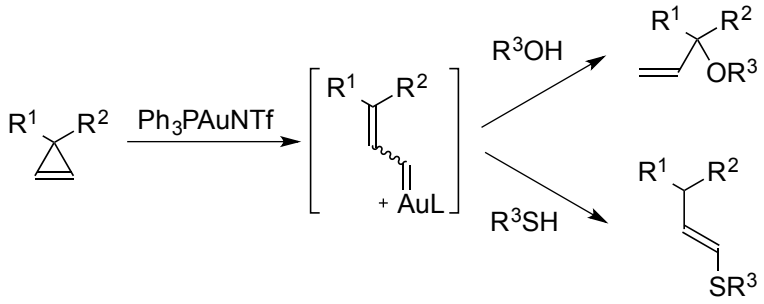
Scheme 7. Cu-Catalyzed Carbometalation/Oxidation/Ring-opening Reaction



I-b-3. Ring-Opening of Cyclopropenes via Vinyl Carbenoid Intermediate

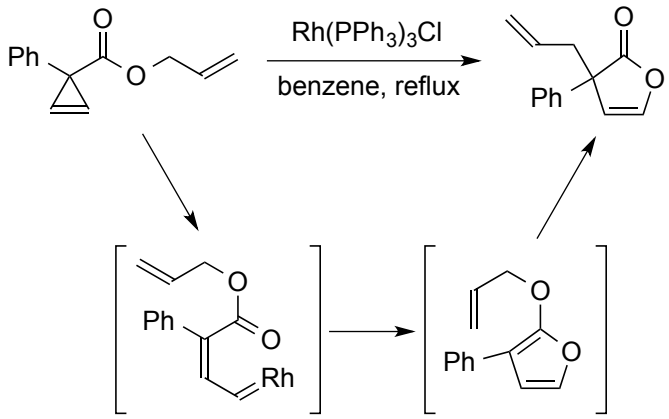
Recently, the unique reactivity of cyclopropene has been reported in the presence of transition metal catalyst, such as Au and Rh. The cyclopropenes gave the vinyl carbenoid intermediate, which reacts with various nucleophiles. In 2008, Lee and co-workers reported Au-catalyzed ring-opening addition of cyclopropenes using alcohols as nucleophile.[11a,b] Furthermore, in 2013, Au-catalyzed addition of thiols was reported.[11c] In these reports, the addition of alcohols and thiols proceeded in differ regioselective manner (Scheme 8).

Scheme 8. Nucleophilic Addition to Au Carbenoid from Cyclopropenes



In 2013, Fox group reported Rh-catalyzed ring-expansion reaction of allylic cyclopropenecarboxylates (Scheme 9).[12] This reaction generated the allyloxyfuran intermediate via Rh carbenoid. Subsequently Claisen rearrangement gave the b,g-butenolides.

Scheme 9. Ring-Expansion of Cyclopropene via Rh carbenoid



II. Allylation Reaction

The nucleophilic reaction using allyl organometallic reagent is one of the most important method for C–C bond formation. In previously, various types of allylation reagents were reported, such as allylzinc, allylboron, allylsilane and allylstannane. However, the variety of these allylation agents was limited in terms of method of preparation.[13] Therefore, extensive studies of allylation reactions were significant in synthetic organic chemistry.

When the allylmetal reagents are used, the addition reactions proceed smoothly in compare with other alkylmetal reagents. In the case of allylmetal reagents, the reactions proceed via six-membered transition state. For instance, the allylation reaction of ketones gave the homoallylic alcohols smoothly via transitionstate **A** (Figure 2). From these convenience, allylation reaction was widely studied by many research groups.

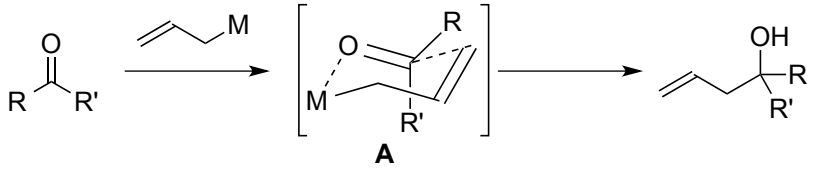
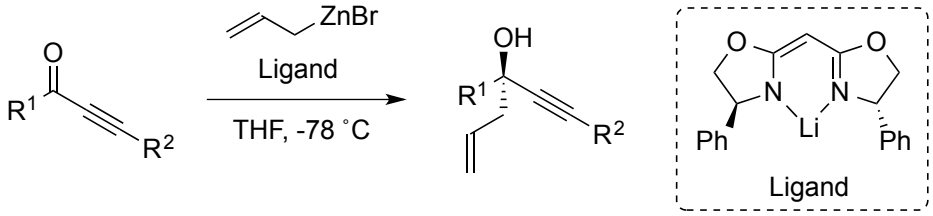


Figure 2. Allylation reaction of ketones

II-a. Allylation Reaction with Allylzinc Reagents

In 1998, Nakamura and co-workers reported the enantioselective allylzincation of alkynyl ketones (Scheme 10).[14] In this reaction, the reactivity and stereoselectivity was controlled by the bisoxazoline ligand. As a result, the tertiary alcohol products were obtained in high yield and ee.

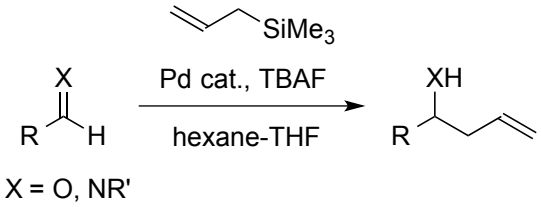
Scheme 10. Enantioselective Addition of Allylzinc to Ketones



II-b. Allylation Reactions with Other Allylation Reagents

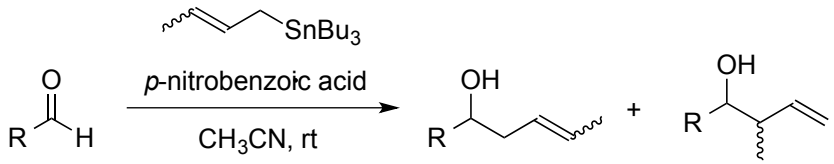
A large number of allylation reactions using allylzinc reagents have been reported to date. However, there are several limitations for the generation of allylzinc reagents, which require somehow unstable allyl halide derivatives. Therefore, development of other allylmetal reagents was necessary. In 1999, Yamamoto and co-workers reported the Pd-catalyzed allylation of aldehydes and imines with allylsilane (Scheme 11).[15] The palladium-TBAF co-catalyst system promoted the allylation reaction to give the desired products smoothly. Furthermore, the use of nontoxic allylsiane is powerful approach for green chemistry.

Scheme 11. Pd-Catalyzed Allylation with Allylsilane



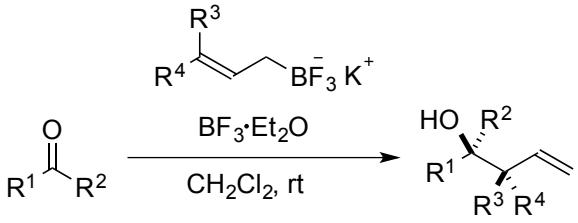
In 2005, Zhao and co-workers reported the allylation of aldehydes with allyltributyltin in the presence of carboxylic acid (Scheme 12).[16] This reaction was promoted to give the various homoallylic alcohols under mild reaction conditions. However, low stereo- and regioselectivity of products was observed.

Scheme 12. Carboxylic Acid Promoted Allylation Reaction with Allyltributyltin



In 2009, Batey and co-workers developed the allylation and crotylation of ketones using potassium organotrifluoroborate salts (Scheme 13).[17] This reaction proceeded with high diastereoselectivity in the presence of Lewis acid. Furthermore, the potassium allyltrifluoroborate salts was air- and water-stable. Therefore, this report could provide the straightforward and scalable methods for allylation and crotylation.

Scheme 13. Allylation and Crotylation with Allylborate

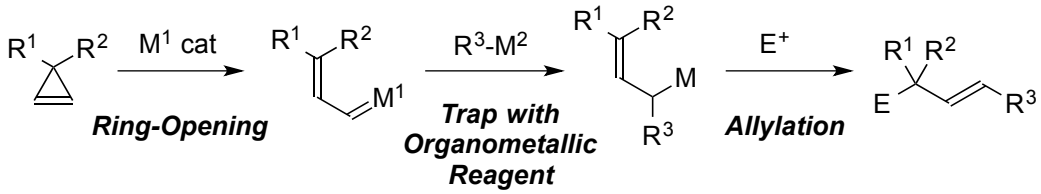


III. The Aim of This Work

Although there are successful results in the C–C bond activation, the rare metal-free C–C bond activation has been rarely reported. Moreover, the reports of ring-opening reaction via carbenoid are limited. Therefore, there are necessary to develop the novel method for C–C bond activation, which gave the various products in single operation.

Herein, I report the tandem allylation reaction with allylmetal intermediate derived from cyclopropene (Scheme 14). The present reaction involves the generation of carbenoid intermediate from cyclopropenes *in situ*, which gives allylmetal inetermediate via trapping reaction with organometallic reagent. The present reaction could afford the various allylated products in single operation.

Scheme 14. Working Hypothesis



Chapter 1. Allylation Reaction of Hydrazones

Chapter 1-1. Tandem Allylation Reaction with Allylzinc Intermediate from Cyclopropene

The cyclopropenone acetal (CPA)[18] was used as a substrate for the generation of vinylcarbene intermediates as described in introduction chapter. As shown in Figure 3, it was considered that CPA could promote the generation of an allylmetal intermediate due to the stabilization by the coordination of an acetal moiety on a Zn center (M = *Zn*). In the present allylation reaction, an allylmetal intermediate could act as a novel acylanion equivalent.

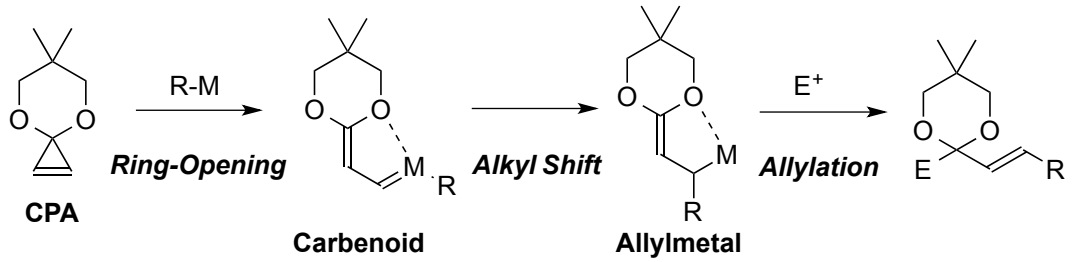


Figure 3. Reaction Design

In the previous report, the vinylcarbene was generated from CPA under thermal conditions to allow the [3+2] cycloaddition(Figure 4).[19] As a preliminary study, the generation of vinylcarbene intermediates under mild conditions was examined (Table 1). When ZnF_2 or $ZnCl_2$ was used, almost the starting material was recovered (entries 1 and 2). $ZnBr_2$ gave a complex mixture (entry 3). In the case of ZnI_2, the ester product was obtained in good yield (entry 4).[20] When $Zn(OAc)_2$ was used, no reaction was observed (entry 5). On the other hand, when I_2 was used, the desired product was not obtained (entry 6). Therefore, ZnI_2 is essential for the present ring-opening of CPA.

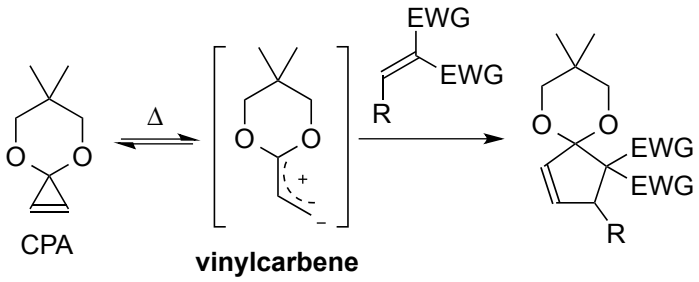
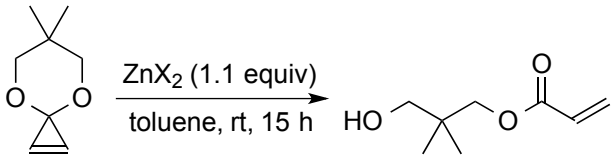


Figure 4. Generation of Vinylcarbene Under Thermal Condition

Table 1. Screening of Zn Reagent for Generation of Zinccarbenoid from CPA

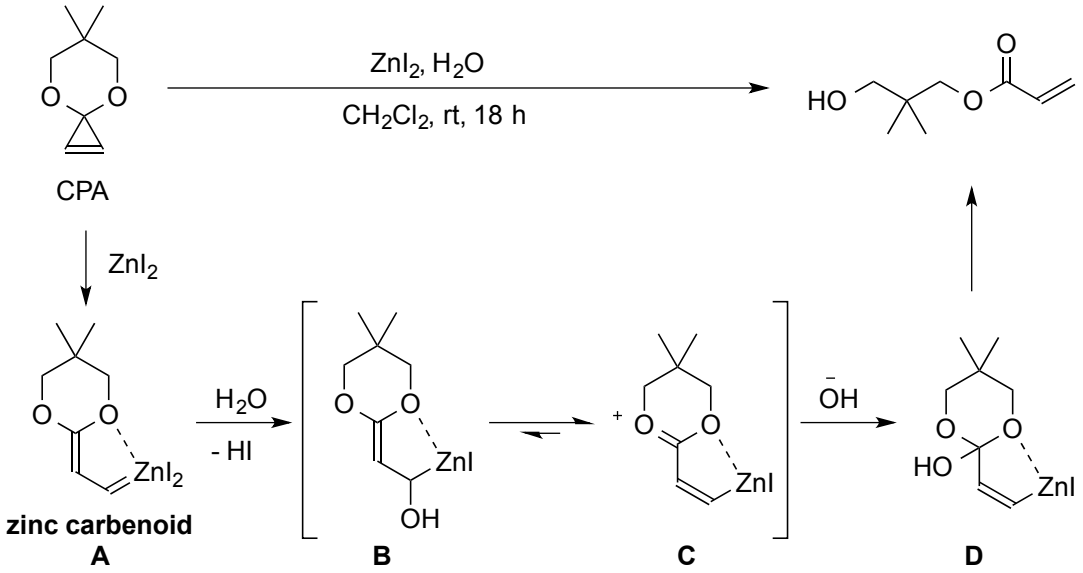


Entry	ZnX_2	Yield/%
1	ZnF_2	trace
2	$ZnCl_2$	trace
3	$ZnBr_2$	complicated
4	ZnI_2	65
5	$Zn(OAc)_2$	nd
6	-[a]	nd

[a] I_2 (1.1 equiv) was used.

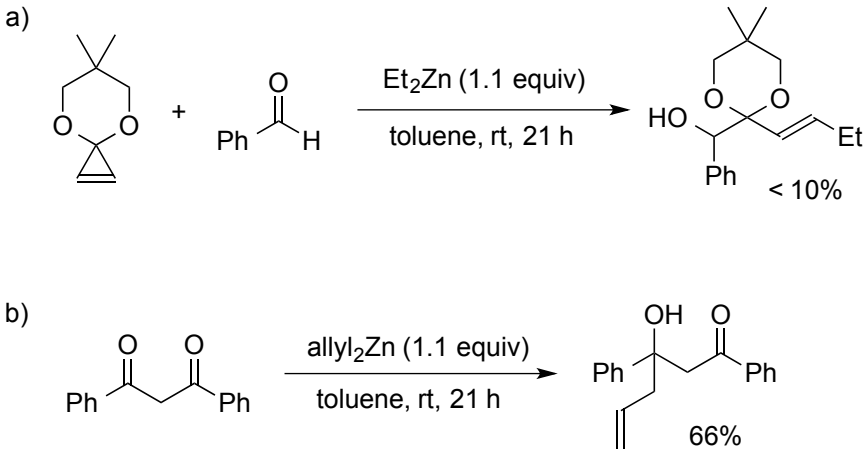
In the present reaction, ZnI_2 might give the ester product via addition of H_2O to zinc carbenoid intermediate (Scheme 15). Namely, the zinc carbenoid **A** was generated from CPA in the presence of ZnI_2. Nucleophilic attack of H_2O allowed the intermediate **D** via intermediate **B** or **C**. Finally, the ring-opening of **D** gave the ester product.

Scheme 15. Proposed Mechanism for Ring-Opening of CPA



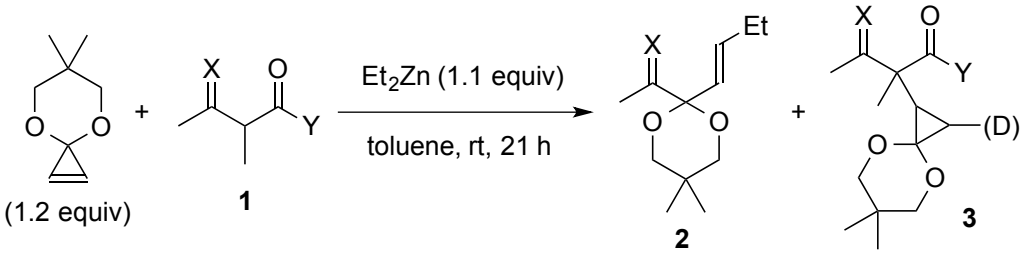
As described in the preliminary study, ZnI_2 is effective for the generation of carbene intermediates from CPA. Therefore, I tried the tandem reaction via a zinc carbenoid intermediate using organozinc reagents and cyclopropenes. Although the allylation reaction to benzaldehyde proceeded, the desired product was obtained in low yield (Scheme 16a). On the other hand, the β-dikeone compound gave the allylated product in good yield (Scheme 16b). This result suggested that the coordination of β-dicarbonyl compound to Zn-center activated the allylzinc reagent. Therefore, the β-dicarbonyl compounds were used as a substrate in the present reaction.

Scheme 16. Addition of Allylzinc Reagents to Carbonyl Compounds



The results of the initial screening of substrates are presented in Table 2. The deprotonation of β-ketoester **1a** by using Et_2Zn and the subsequent addition to CPA gave a complicated mixture (entry 1). The reaction of imine **1b** derived from **1a** under the same reaction conditions also gave a complicated mixture (entry 2). The reaction of imine **1c** derived from β-ketoamide and allylamine predominantly gave cyclopropane **3c** without a ring-opening reaction of CPA; the reaction was quenched using D_2O gave product **3c** with approximately 60% deuteration at the sp^3 carbon atom of cyclopropane (entry 3).[21] In sharp contrast, the reaction of hydrazone **1d** derived from β-ketoamide gave the desired hydrazone **2d** in low yield (entry 4). Thus, the use of hydrazone seemed to be important in promoting the tandem reaction in Figure 1. The subtle difference in the substituent at the C=N bond produced a dramatic change in the reaction pathway.

Table 2. Screening of Substrates



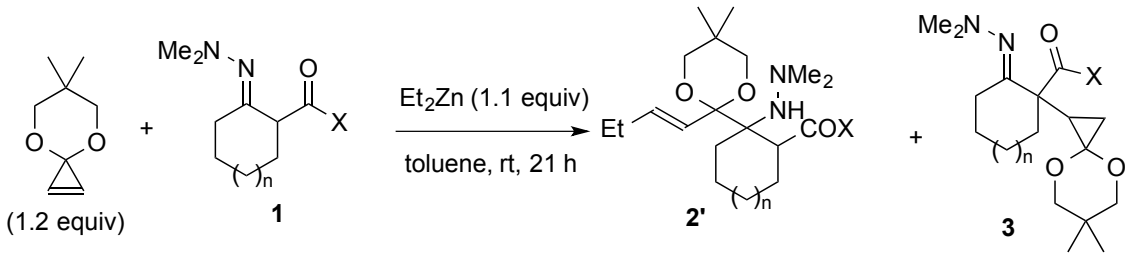
Entry	X, Y	Yield/%
1	O, OEt (**1a**)	complicated
2	allyl-N, OEt (**1b**)	complicated
3	allyl-N, NMe_2 (**1c**)	**2c**: nd, **3c**: 62[a]
4	Me_2N-N, NMe_2 (**1d**)	**2d**: 31, **3d**: nd

[a] Single diastereomer was obtained. The geometry could not be determined.

Table 3 shows the effect of the cyclic hydrazones. Cyclohexanone derivative **1e** bearing dimethylamide moiety gave a mixture of corresponding products **2'e** and **3e**; cyclic substrates gave the corresponding sterically congested product **2'e** through allylation of the hydrazone moiety, which generally seems to be sluggish (entry 1). The cyclohexanone derivative bearing a diethylamide moiety improved the yield and selectivity; product **2'f** was obtained as a single diastereomer and a small amount of **3f**

was obtained (entry 2). When the substrate bearing ethylester moiety was used, **3g** was obtained in high yield; however, desired product **2'g** was not obtained at all (entry 3). The deprotonation of activated methylene would promote the cyclopropylation to give the product **3g**. The reaction of cyclopentanone derivative **1h** gave unidentified products (entry 4). Cycloheptanone derivative **1i** gave a complicated mixture (entry 5). Therefore, cyclohexanone derivatives bearing a diethylamide group were chosen as initial substrates.

Table 3. Effect of Cyclic Substrates



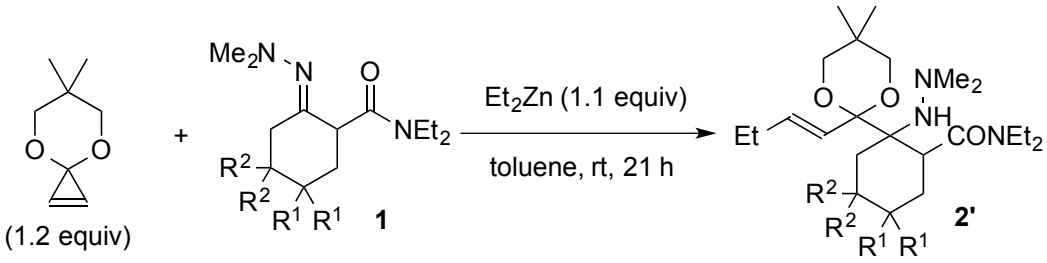
Entry	n, X	Yield/%
1	1, NMe_2 (**1e**)	**2'e**: 40,[a] **3e**: 20[a]
2[b]	1, NEt_2 (**1f**)	**2'f**: 69,[c] **3f**: 8
3	1, OEt (**1g**)	**2'g**: nd, **3g**: 96[c]
4	0, NEt_2 (**1h**)	unidentified product
5	2, NEt_2 (**1i**)	complicated

[a] Yield was determined by NMR spectroscopy as a result of the inseparable mixture.
[b] The corresponding β-ketoamide did not give the product. [c] Single diastereomer was obtained.

We focused on the unprecedented reaction by using hydrazone derivatives **1f** and **1j–v** and CPA to give densely functionalized and sterically congested cyclohexylamines **2'f** and **2'j–v** as single diastereomers, respectively (Table 4). The reaction proceeded even at room temperature, and the low conversion gave low yields of products **2'**. Only hydrazone **1f** gave cyclopropane **3f** in low yield as a byproduct, and generally hydrazones **1j–v** bearing substituents did not give cyclopropane derivatives **3i–u** at all. A simple substituent at the 4-position of the cyclohexane moiety did not affect the yields of the products; products **2'f** and **2'j–n** were obtained in yields of 60–72% (entries 1–6). In contrast, heteroatom substituents slowed the reaction rate; benzyl ether **1o** gave desired product **2'o** in 28% yield (entry 7). These low yields were attributed to

the low conversion of the substrates. The use of **1p** bearing dimethyl substituent gave desired product **2'p** in 82% yield (entry 8). The reaction of dioxolane **1q** gave desired product **2'q** in moderate yield; low conversion was observed (entry 9). The incorporation of an exomethylene moiety in **1r** diminished the yield of product **2'r** (entry 10). The use of **1s**, **1t**, and **1u** gave desired products **2's**, **2't**, and **2'u** (entries 11–13). In contrast, the reaction of **1v** did not give the desired product; 1,3-diaxial repulsion seems to inhibit the allylation reaction (entry 14). A fine single crystal was obtained from product **2's**, and its relative configuration was ascertained.

Table 4. Scope of Substrates

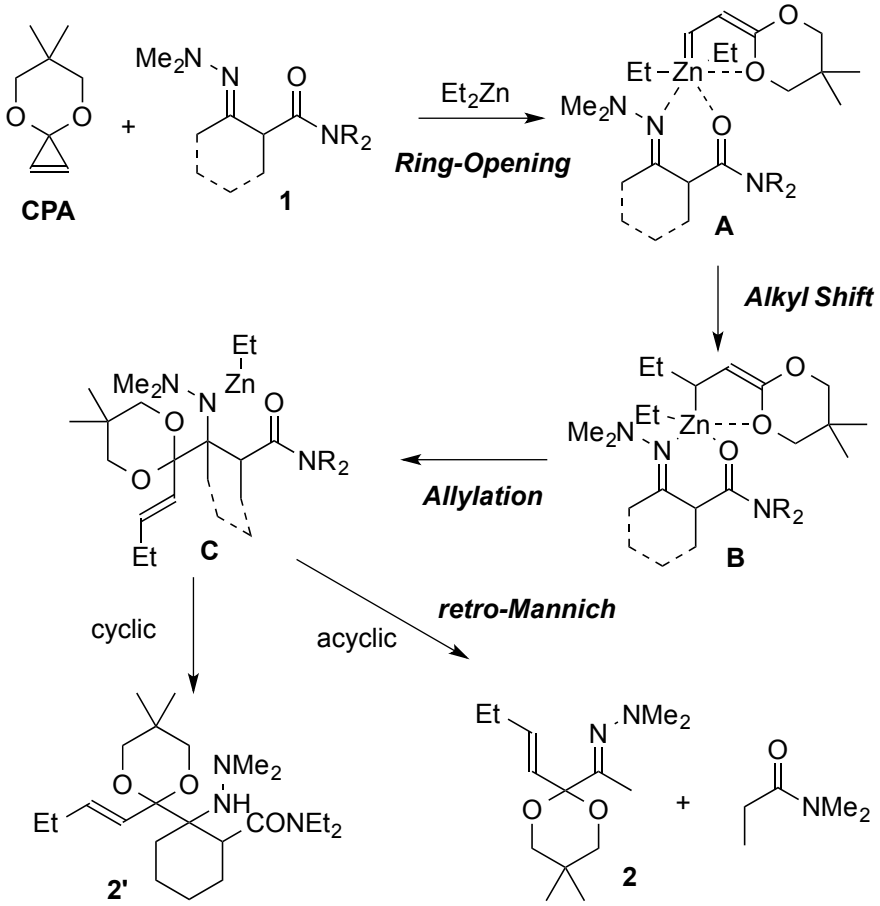


Entry	R^1, R^2	Yield/%
1	$R^1 = R^2 = H$ (**1f**)	69 (**2'f**)[a]
2	R^1 = Me, H; R^2 = H (**1j**)	60 (**2'j**)
3	R^1 = *n*-C_3H_7, H; R^2 = H (**1k**)	63 (**2'k**)
4	R^1 = *n*-C_5H_{11}, H; R^2 = H (**1l**)	71 (**2'l**)
5	R^1 = *t*-Bu, H; R^2 = H (**1m**)	72 (**2'm**)
6	R^1 = Ph, H; R^2 = H (**1n**)	66 (**2'n**)
7	R^1 = OBn, H; R^2 = H (**1o**)	28 (**2'o**)
8	R^1 = Me, Me; R^2 = H (**1p**)	82 (**2'p**)
9	R^1 = -$O(CH_2)_2O$-; R^2 = H (**1q**)	40 (**2'q**)
10	$R^1 = CH_2$; R^2 = H (**1r**)	26 (**2'r**)
11	R^1 = H; R^2 = Me, H (**1s**)	73 (**2's**)
12	R^1 = H; R^2 = Ph, H (**1t**)	59 (**2't**)
13	R^1 = H; R^2 = 4-BrC_6H_4, H (**1u**)	31 (**2'u**)
14	R^1 = H; R^2 = Me, Me (**1v**)	trace

[a] When Me_2Zn was used instead of Et_2Zn, the corresponding product **2'f-Me** was obtained in 20% yield.

The proposed mechanism is shown in Scheme 17. The CPA and an organozinc reagent gave the carbenoid intermediate **A** in the presence of hydrazoneamide. The allylzinc intermediate **B** was generated by intramolecular alkyl shift.[22] In the case of cyclic substrate, sequential allylation reaction gave desired hydrazine product **2'**. On the other hand, when the acyclic product was used, the hydrazone product **2** was obtained via retro-Mannich-type cleavage of amide moiety.[23]

Scheme 17. Proposed Mechanism



The diastereoselectivity could be derived from the relative configuration of the allylic and amide moiety at the equatorial positions (Figure 5). The equatorial positions of allyic and amide are the most stabilized configuration in terms of steric hindrance. Furthermore, this configuration is the most suitable for the coordination to Zn center by amide after allylation reaction.

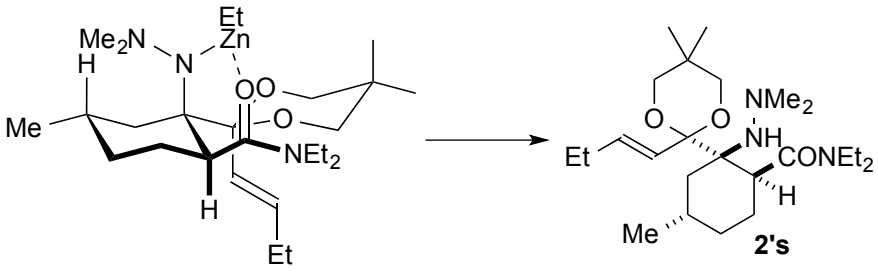


Figure 5. Model for Diastereoselectivity of 2's

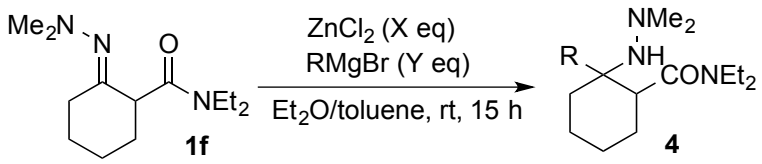
I achieved the tandem allylation reaction using allylzinc intermediate from cyclopropenes. The present reaction proceeded to give densely functionalized and sterically congested cyclohexylamines as a single diastereomer, respectively.

Chapter 1-2. Allylation Reaction with Diallylzinc

In the tandem allylation reaction, the allylzinc intermediates from cyclopropenes promoted the nucleophilic addition to unactivated hydrazones smoothly.[24] Therefore, the use of allylzinc reagent could allow the allylation of various hydrazones. Herein, the allylation reaction of β-hydrazoneamides with diallylzinc was examined.

I selected hydrazoneamide **1f** as a model substrate for the optimization of the reaction conditions using allylzinc reagents (Table 5). Allylzinc reagents were prepared from allylmagnesium bromide and $ZnCl_2$ in ether as described in the previous report.[25] The use of diallylzinc instead of an allylzinc reagent increased the yield of product **4f** (entries 1 and 2). When allylmagnesium bromide was used without $ZnCl_2$, the allylation of hydrazone didn't proceed at all (entry 3). Formation of magnesium enolate by deprotonation of **1f** due to the higher basic character of Grignard reagent might occur. The use of a catalytic amount of $ZnCl_2$ with allylmagnesium bromide gave the desired product **4f** in low yield (entry 4). The allylation of hydrazone requires diallylzinc, not *in situ* generated zincate complexes, such as $(allyl)_3ZnMgCl$.[26] When ethylmagnesium bromide was used instead of allylmagnesium bromide, the adduct was not obtained (entry 5). Therefore, six-membered transition state with hydrazone seems to be essential to promote the present reaction.

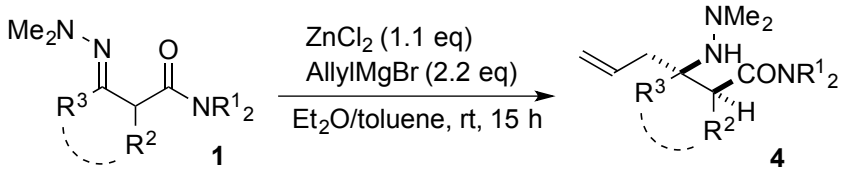
Table 5. Optimization of Reaction Conditions for Allylation Reaction of Hydrazone

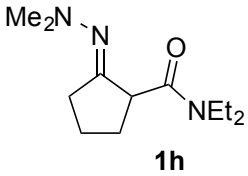
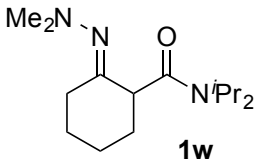
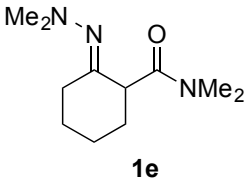
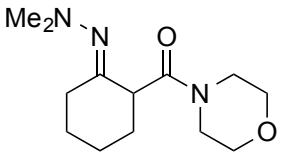
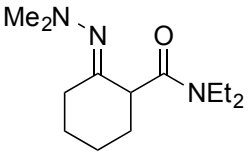
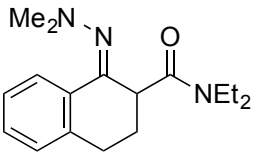
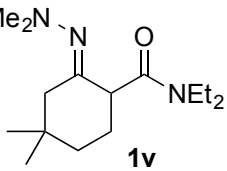
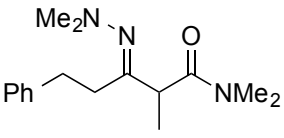


Entry	X	R	Y	Yield / %
1	1.1	Allyl	1.1	58 (**4f**)
2	1.1	Allyl	2.2	86 (**4f**)
3	-	Allyl	2.2	nd
4	0.1	Allyl	2.2	< 8 (**4f**)
5	1.1	Et	2.2	nd

Under the optimized reaction conditions, allylation of various hydrazones using diallylzinc was performed (Table 6). When five-membered cyclic hydrazone-amide **1h** was used as a substrate, the allylated product **4h** was obtained in 31% yield. The previous report for the tandem allylation did not allow the desired product at all using **1h**; thus, the use of **1h** might not be a suitable ligand for the generation of an allylzinc intermediate as described in chapter 1-1. The cyclohexanone derivatives **1e, 1f, 1w,** and **1x** bearing various type of amide group gave the desired products **4e, 4f, 4w,** and **4x** in good to high yields with high diastereoselectivities (entries 1-3, and 5, 6). However, the use of 5,5-dimethyl cyclohexanone derivative **1v** gave the desired product **4v** in only 21% yield due to the 1,3-strain of hydrazine (entry 4). On the other hand, benzene ring-fused substrate **1y** gave the corresponding product **4y** in moderate yield (entry 7). When the acyclic substrate **1z** was used, allylated product **4z** was not obtained (entry 8). ESI-TOF mass spectrometry showed the generation of **4z**, but the purification by silica gel column chromatography decomposed the desired product.

Table 6. Scope of Substrates



Entry	substrate	Yield/ %	Entry	substrate	Yield/%
1	 **1h**	31 (**4h**)	5	 **1w**	77 (**4w**)
2	 **1e**	64 (**4e**) dr = 9:1	6	 **1x**	81 (**4x**)
3	 **1f**	86 (**4f**)	7	 **1y**	53 (**4y**)
4	 **1v**	21 (**4v**)	8	 **1z**	complicated mixture

The desired product **4** was obtained diastereoselectively. The NOE study showed the interaction between H^a (terminal of allyl) and H^b (-NEt_2); the configuration of product is described in Figure 6.

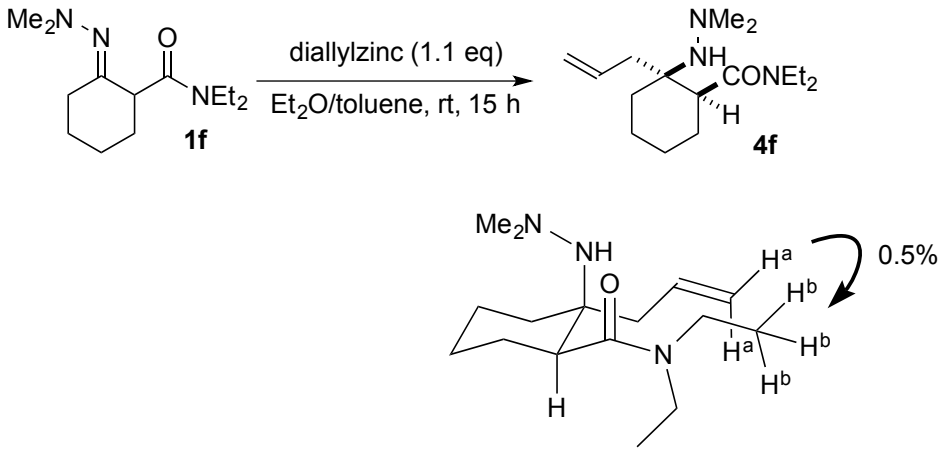
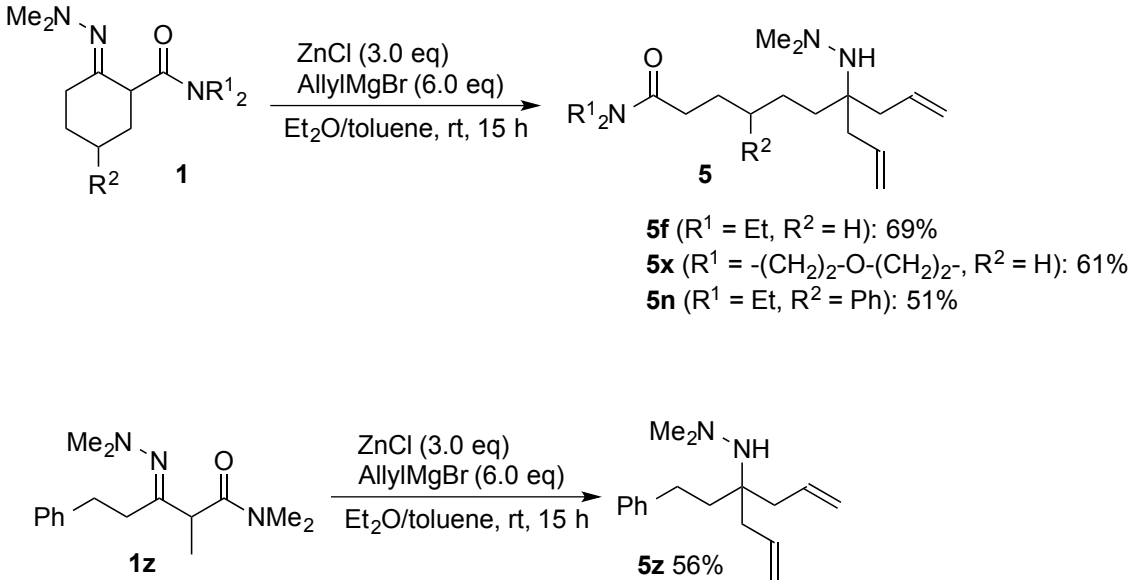


Figure 6. NOE Study of Product 4f

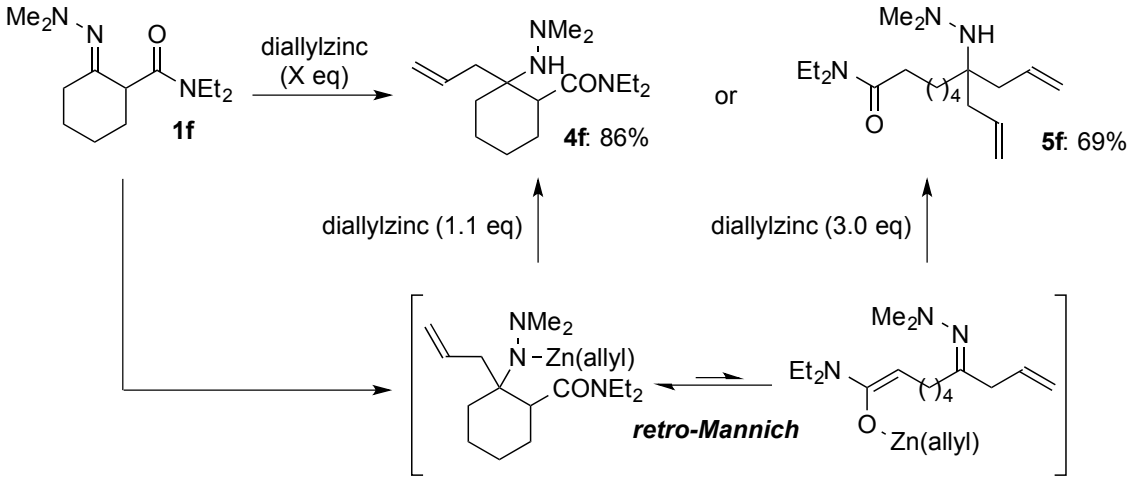
To elucidate the rationale for the retro-Mannich type reaction, the tandem addition reaction to the hydrazone was examined after the allylation reaction. The use of an excess amount of diallylzinc gave the diallylated product **5** (Scheme. 18). Cyclic substrates **1f**, **1x**, and **1n** gave the acyclic diallylated product **5f**, **5x**, and **5n** in good yields. Furthermore, the acyclic substrate **1z** gave the diallylated product **5z** via cleavage of amide moiety. In the case of **1z**, allylated product **4z** was not isolated due to concerted retro-Mannich reaction even if an equivalent of diallylzinc was used. Namely, the acyclic substrate promoted the retro-Mannich reaction in the presence of organozinc reagent. The present result is consistent with that the hydrazone product **2d** was obtained from **1d** in the tandem allylation reaction (Table 2).

Scheme 18. Diallylation of β-Hydrazoneamide



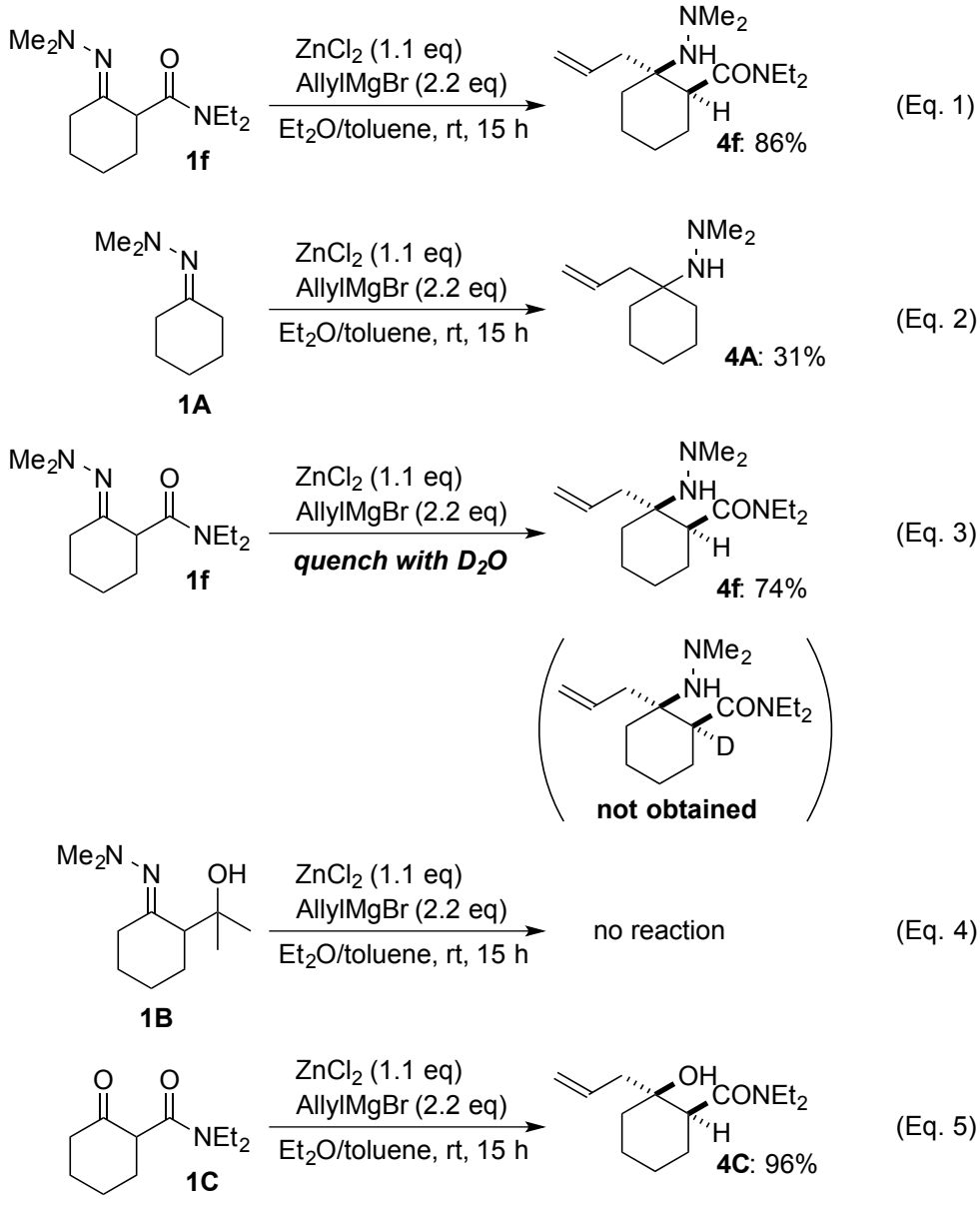
The present result indicated that the retro-Mannich type reaction took place after the allylation reaction of hydrazone moiety. Consequently, the subsequent addition of another diallylzinc to hydrazone proceeded to give diallylated **5f** (Scheme 19). Therefore, the deprotonation of **1f** might not occur in the present reaction.

Scheme 19. Allylation and Diallylation of β-Hydrazoneamide



To gain a mechanistic insight of the present allylation reaction, the control experiments were carried out. The coordination of an amide moiety to a Zn center seems to be crucial for the activation of diallylzinc (eqs. 1 and 2). I wondered that the allylation proceeded via the deprotonation of substrate **1** or not. The reaction was

quenched with deuterium oxide gave non-deuterated product **1f**, indicating that the deprotonation reaction did not occur (eq. 3). When hydrazone **1B** bearing a hydroxyl group instead of an amide group was used as a substrate, the allylation reaction did not proceed (eq. 4). These results showed the coordination of a hydrazoneamide to a Zn center is essential for allylation of hydrazone. In a similar manner, β-keto amide **1C** induced the allylation reaction in high yield (eq. 5). Thus, the amide moiety would be required for the generation of allylzinc intermediates derived from cyclopropenes using dialkylzinc (Chapter 1-1).



I have developed the allylation reaction of hydrazones and diallylation reaction of dicarbonyl compounds with diallylzinc. The diallylzinc was activated by coordinative substrates and the highly efficient allylation reaction of unactivated carbonyl derivatives was achieved.

Chapter 2 Tandem Allylation Reaction of Carbonyl Derivatives

Chapter 1 shows the tandem allylation reaction using cyclopropenes and organozinc reagents to give the hydrazine products. The nucleophilic attack of allylzinc intermediates to other external electrophiles would be possible in the presence of β-hydrazoneamide as a ligand for the generation of allylzinc intermediate. I report here the β-hydrazoneamide-catalyzed tandem allylation reaction of aldehydes and an aldimine as 3-component reactions in a single operation (Figure 7).

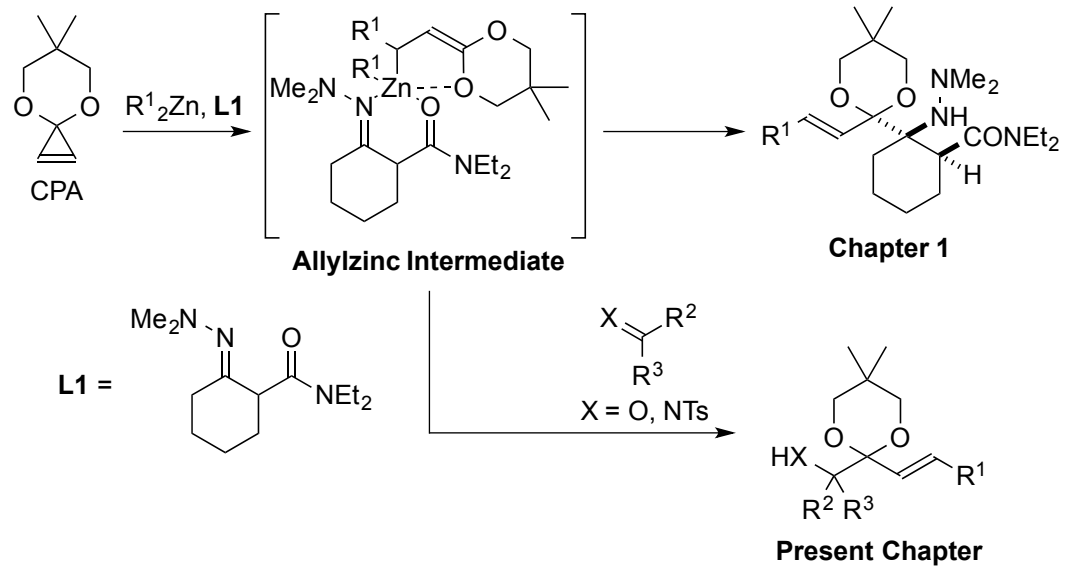
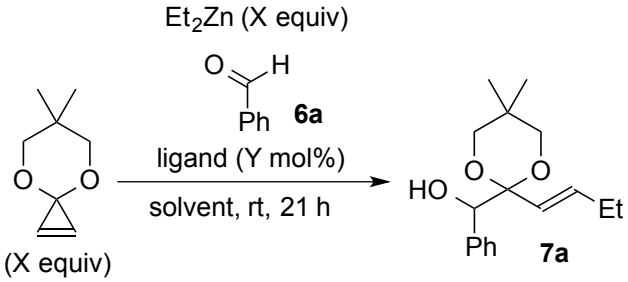


Figure 7. Tandem Allylation Reaction Using Cyclopropene and Organozinc Reagent

The reaction conditions were examined for the β-hydrazoneamide-mediated or -catalyzed tandem allylzincation of benzaldehyde (**6a**) using diethylzinc and CPA (Table 7). The reaction without a ligand gave the desired product **7a** in poor yield (entry 1). The use of cyclic hydrazoneamide **L1** as a ligand gave the product **7a** in moderate yield; other ligands **L2** or **L3** promoted unidentified side reactions (entries 2–4). The ligands gradually gave a trace amount of byproducts via allylation to hydrazone and/or cyclopropylation, as described in Chapter 1. The use of acyclic β-hydrazoneamide **L4** or **L5** gave the product **7a** in lower yields (entries 5 and 6). On the other hand, β-ketoamide **L6**, β-hydroxyhydrazone **L7**, amino alcohol **L8**, and *N*,*N*,*N*',*N*'-tetramethylethylenediamine (TMEDA) did not give the product **7a** (entries 7–10). Therefore, the amounts of **L1**, diethylzinc, and CPA were examined. The reaction in the presence of a catalytic amount of **L1** (15 mol %) gave **7a** in 56% yield (entry 11). When the reaction was carried out at 0 °C, the yield of **7a** was decreased (entry 12). Further screening of the reaction conditions in the presence of **L1** (25 mol %) showed that the reaction using diethylzinc (1.3 equiv) and CPA (1.3 equiv) gave the product **7a** in 76% yield (entries 13–17). The use of a coordinative solvent slowed the reaction (entries 18–23).

Table 7. Optimization of Reaction Conditions



Entry	ligand	solvent	X	Y	Yield/%
1	-	toluene	1.1	0	< 10
2	**L1**	toluene	1.1	110	44
3	**L2**	toluene	1.1	110	nd
4	**L3**	toluene	1.1	110	20
5	**L4**	toluene	1.1	110	41
6	**L5**	toluene	1.1	110	trace
7	**L6**	toluene	1.1	110	nd
8	**L7**	toluene	1.1	110	nd
9	**L8**	toluene	1.1	110	nd
10	TMEDA	toluene	1.1	110	nd
11	**L1**	toluene	1.1	15	56
12[a]	**L1**	toluene	1.1	15	< 33
13	**L1**	toluene	1.1	25	47
14	**L1**	toluene	1.2	25	70
15	**L1**	toluene	1.3	25	76
16	**L1**	toluene	1.4	25	65
17	**L1**	toluene	1.5	25	61
18	**L1**	toluene	1.3	25	63
19	**L1**	hexane	1.3	25	65
20	**L1**	THF	1.3	25	< 7
21	**L1**	Et_2O	1.3	25	14
22	**L1**	MTBE	1.3	25	38
23	**L1**	CH_2Cl_2	1.3	25	19

[a] The reaction was performed at 0 ˚C.

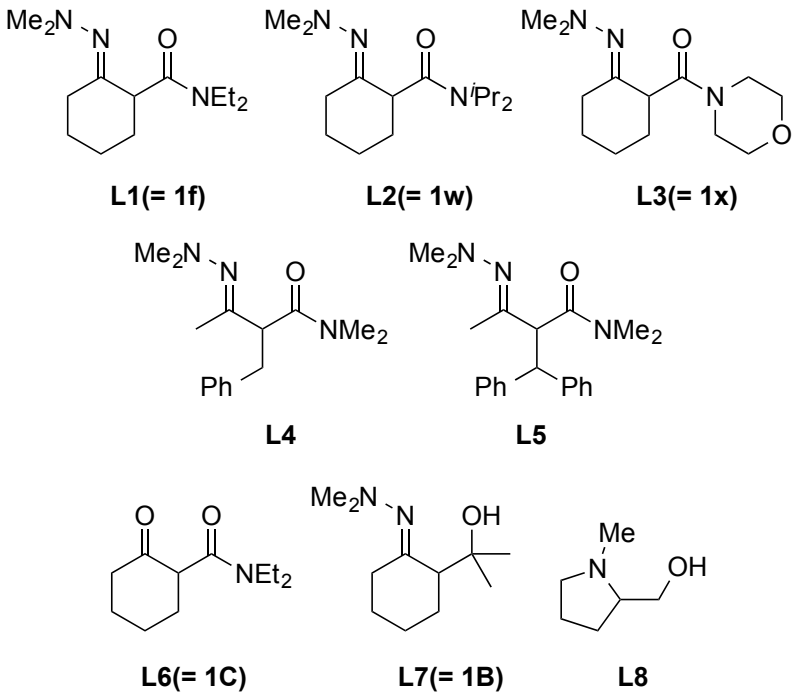
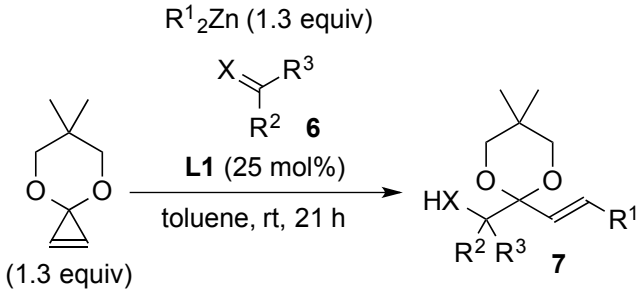


Figure 8. List of Ligands

Under the optimized conditions, a catalytic tandem allylation reaction was performed using various carbonyl derivatives (Table 8). The reaction typically gave the (*E*)-isomer as a sole or major product along with less than 5% of the (*Z*)-isomer. When Me_2Zn or *i*-Pr_2Zn was used instead of Et_2Zn, the allylation reaction of benzaldehyde (**6a**) proceeded to give the desired products **7a-Me** or **7a-*i*-Pr** (entries 2 and 3). When Ph_2Zn was used, the desired product was obtained in low yield, but the reaction was not reproducible. The reactions of 2-, 3-, or 4-methylbenzaldehyde (**6b–d**) gave the desired products **7b–d** in good yields (entries 4–6). When aromatic aldehydes **6e–g** bearing an electron-donating or -withdrawing group on the benzene ring were used, the corresponding products **7e–g** were obtained in moderate to good yields, respectively (entries 7–9). The use of 1- or 2-naphthaldehyde (**6h** or **6i**) decreased the yields of products **7h** or **7i** (entries 10 and 11). A heteroaromatic aldehyde, 2-furfural (**6j**), was available (entry 12). The use of aliphatic aldehydes, such as dihydrocinnamaldehyde (**6k**), cinnamaldehyde (**6l**), and cyclohexanecarboxaldehyde (**6m**), gave the products **7k–m** in good yields (entries 13–15). The reaction of bulky pivalaldehyde (**6n**) diminished the yield of product; the acetal moiety partially decomposed on silica gel to give **7n**. The acidic deprotection after the reaction gave the product **7n** as a ketone (entry 16). The use of *N*-tosylimine (**6o**) gave the corresponding amine **7o** in moderate yield (entry 17). The reaction of ketone derivatives was examined, and the use of acetophenone gave the products in poor yield as a nonisolable mixture. In contrast, the use of electronically activated 2,2,2-trifluoroacetophenone (**6p**) gave the desired product **7p** in 28% yield (entry 18).

Table 8. Scope of Substrates

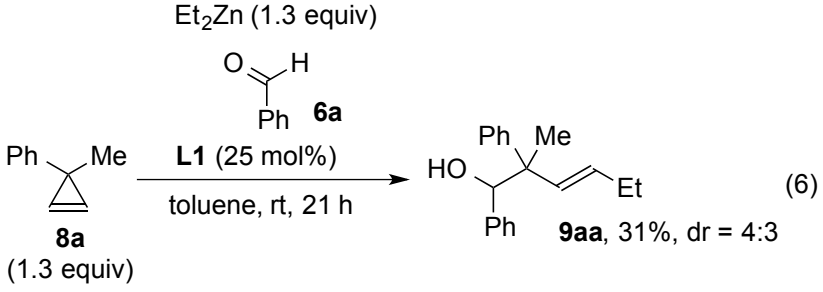


Entry	R^1	R^2, R^3, X	Yield/%
1	Et	Ph, H, O (**6a**)	76 (**7a**)
2	Me	Ph, H, O (**6a**)	48 (**7a-Me**)
3	*i*-Pr	Ph, H, O (**6a**)	68 (**7a-*i*-Pr**)
4	Et	2-MeC_6H_4, H, O (**6b**)	62 (**7b**)
5	Et	3-MeC_6H_4, H, O (**6c**)	68 (**7c**)
6	Et	4-MeC_6H_4, H, O (**6d**)	71 (**7d**)
7	Et	4-$CF_3C_6H_4$, H, O (**6e**)	70 (**7e**)
8	Et	4-$MeOC_6H_4$, H, O (**6f**)	52 (**7f**)
9[a]	Et	4-FC_6H_4, H, O (**6g**)	56 (**7g**)
10	Et	1-naphthyl, H, O (**6h**)	48 (**7h**)
11	Et	2-naphthyl, H, O (**6i**)	trace (**7i**)
12	Et	2-furyl, H, O (**6j**)	74 (**7j**)
13	Et	2-phenylethyl, H, O (**6k**)	73 (**7k**)
14	Et	2-phenylethenyl, H, O (**6l**)	68 (**7l**)
15	Et	*c*-Hex, H, O (**6m**)	77 (**7m**)
16	Et	*t*-Bu, H, O (**6n**)	35 (**7n**)[b]
17	Et	Ph, H, NTs (**6o**)	41 (**7o**)
18	Et	Ph, CF_3, O (**6p**)	28 (**7p**)

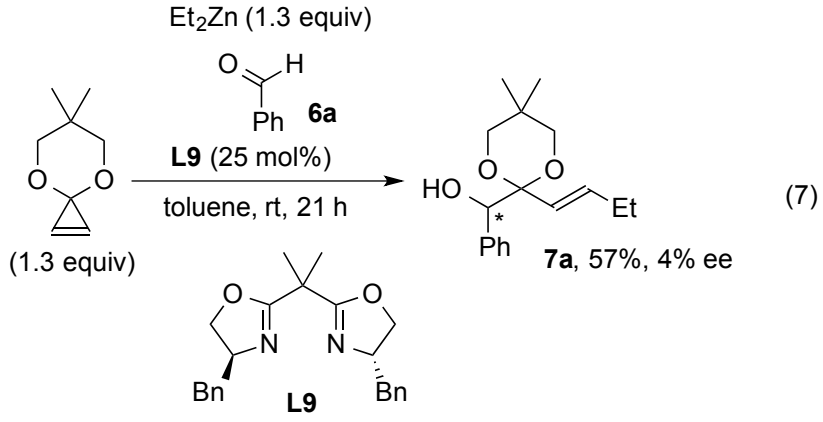
[a] **L1** (2 equiv), Et_2Zn (2 equiv), and CPA (2 equiv) were used. [b] The product was isolated as a ketone after deprotection of acetal moiety.

The reaction using 3,3-dialkyl cyclopropene **8a** gave the product **9aa** in low yield as a nonisolable diastereomeric mixture (eq 6). The present result suggested that coordination of an acetal moiety on a Zn center is critical for the generation and stabilization of an allylzinc intermediate. Therefore, CPA is the most suitable substrate in the present reaction.

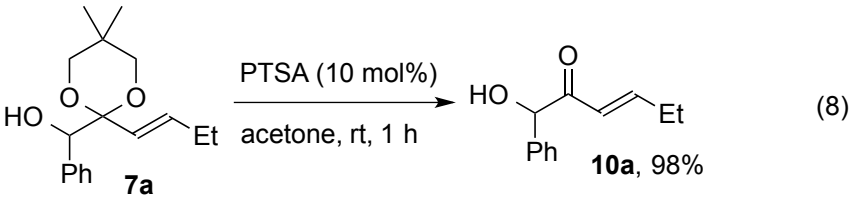
In the past, Nakamura and co-workers reported the enantioselective allylzincation of ketones using a bisoxazoline ligand as described in introduction chapter. Therefore, I tentatively examined the use of bisoxazoline **L9** as a chiral ligand for the asymmetric allylation reaction. The desired product **7a** was obtained, but the enantioselectivity was poor (eq 7). Deprotection of the acetal moiety of product **7a** proceeded in the presence of *p*-toluenesulfonic acid (PTSA) to give the corresponding α-hydroxy ketone **10a** in almost quantitative yield (eq 8).



(6)



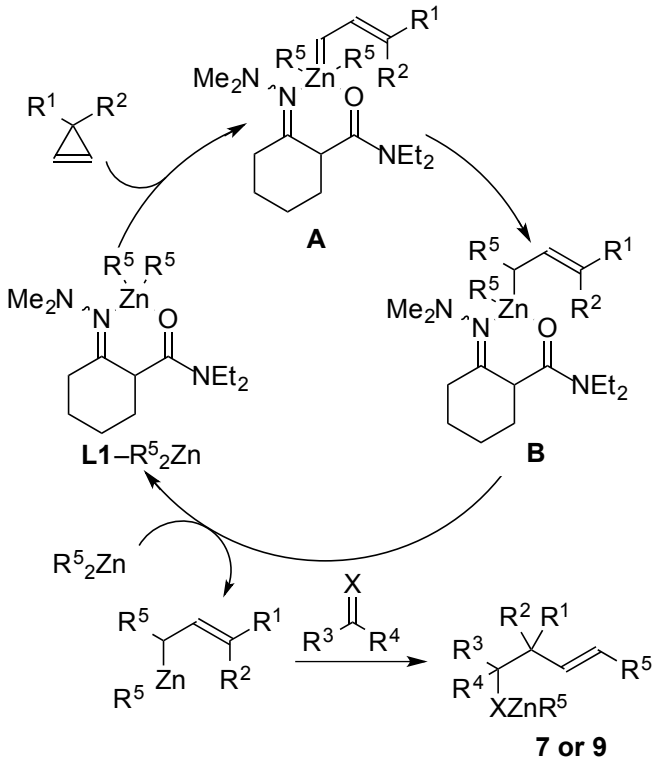
(7)



(8)

A plausible mechanism for the present reaction is shown in Scheme 20. Initial ring-opening of a cyclopropene in the presence of **L1** results in the formation of the zinc carbenoid **A** like the reaction with ZnI_2 described in chapter 1. Subsequent intramolecular alkyl shift generates the allylzinc intermediate **B**. The allylzincation of an aldehyde proceeds to give the desired product **8**, while the elimination of **L1** might occur. The oxygen atoms in CPA seem to play an important role in obtaining the desired products in good yields, since 3-methyl-3-phenyl- cyclopropene gave the desired product in low yield along with the generation of unidentified byproducts.

Scheme 20. Plausible Mechanism for Tandem Allylation Reaction



In conclusion, a catalytic tandem allylation of aldehydes, an aldimine, and a ketone with an allylzinc intermediate via the ring-opening of cyclopropene was achieved in the presence of a β-hydrazoneamide as a ligand, which is a substrate in chapter 1. The present allylzinc intermediate acts as an α,β-unsaturated acylanion equivalent and thus gives a wide variety of functionalized homoallyllic alcohols or amine in a one-pot procedure.[27]

Chapter 3. Cu-Catalyzed Carbometalation of Cyclopropenes

Chapter 1 and 2 describes that the tandem allylation reaction proceeded via carbene intermediates as a working hypothesis. However, there is another possibility; the initial step of the allylation reaction would be carbozincation of cyclopropenes (Figure 9). There are several reports for the ring-opening of cyclopropylmetal intermediates after carbometalation of cyclopropenes (Figure 10).[28]

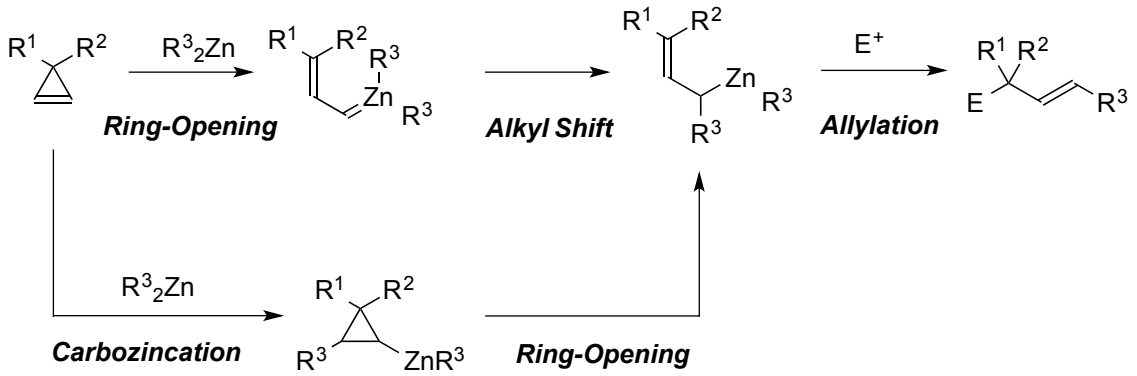


Figure 9. Another Possible Pathway of Tandem Alylation Reaction

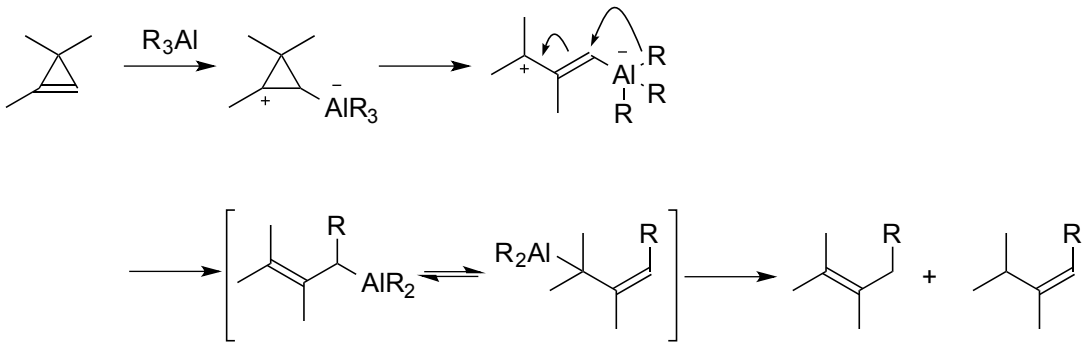


Figure 10. Carbometalation/Ring-Opening Sequence with Organoaluminium Reagent

Therefore, I examined the generation of cyclopropylzinc intermediates via carbozincation of various cyclopropenes for the subsequent ring-opening to give allylzinc intermediates. Previously, Cu-catalysts have allowed the carbometalation of alkyne to give the multifunctional alkenes (Figure 11a).[29] Furthermore, Cu-catalyzed carbometalation of cyclopropenes has been reported by some groups. In these reports, the hydroxyl group of cyclopropene is essential for high reactivity and stereoselectivity (Figure 11b).[30] In the present chapter, an efficient ligand for the Cu-catalyzed carbometalation of unfunctionalized cyclopropenes is shown for the elucidation of the generation of allylmetal intermediatesvia the ring-opening (Figure 12).[31]

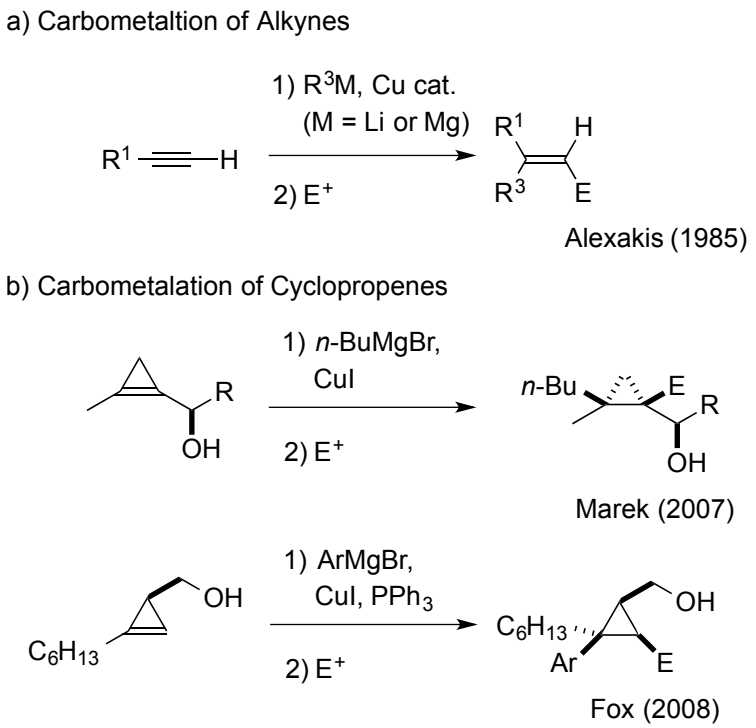


Figure 11. Cu-Catalyzed Carbometalation

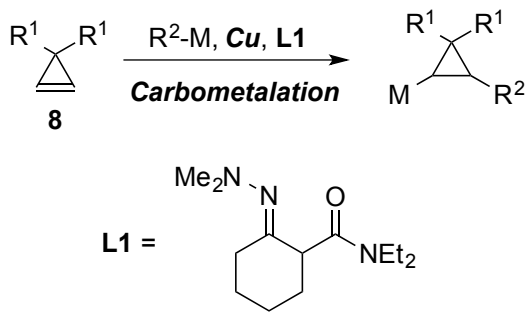
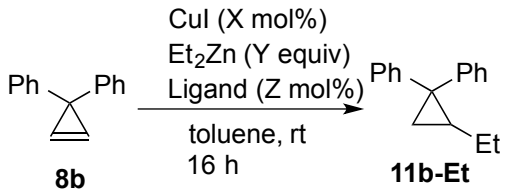


Figure 12. Carbometalation of Cyclopropenes

The reaction conditions were examined using 3,3-diphenylcyclopropene (**8b**) as a substrate (Table 9). We found that the reaction of **8b** and Et_2Zn (3 equiv) in the presence of CuI (20 mol%) and **L1** (25 mol%) promoted the carbozincation to give the desired product **11b-Et** in high yield (entry 1). The reaction without copper catalyst or ligand gave **11b-Et** in low yields (entries 2 and 3). When other ligands, such as **L4**, **L6**, and *N*,*N*,*N'*,*N'*-tetramethylethylenediamine (TMEDA), were used, the product **11b-Et** was obtained in good yields (entries 4–6). Further optimization of reaction conditions showed that the use of CuI (5 mol%), Et_2Zn (2 equiv) and **L1** (7.5 mol%) gave the desired product **11b-Et** in 86% yield (entries 7–10). When Grignard reagent, EtMgBr, was used instead of Et_2Zn in the presence of CuI and **L1**, the product **11b-Et** was obtained in high yields (entries 11 and 12). Thus, the present catalyst is suitable for the use of organozinc and Grignard reagents.

Table 9. Optimization of Reaction Conditions



Entry	X	Y	Ligand	Z	Yield/%
1	20	3.0	**L1**	25	91
2	-	1.5	**L1**	25	nd
3	20	3.0	-	-	< 30
4	20	3.0	**L4**	25	87
5	20	3.0	**L6**	25	73
6	20	3.0	TMEDA	25	77
7	10	3.0	**L1**	15	85
8	5	3.0	**L1**	7.5	89
9	5	2.0	**L1**	7.5	86
10	1	2.0	**L1**	3	< 40
11[a]	5	2.0	-	7.5	56
12[a]	5	2.0	**L1**	7.5	81

[a] EtMgBr was used instead of Et_2Zn.

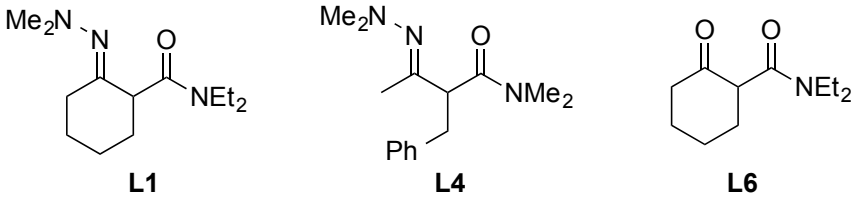
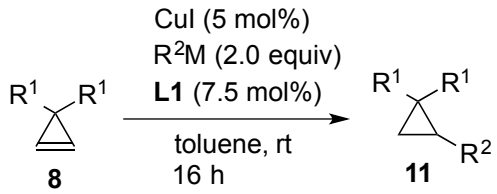


Figure 13. List of Ligands

Under the optimized reaction conditions, the carbometalation of **8b** was performed using various organometallic reagents (Table 10). Although Et_2Zn gave the desired product in high yield (entry 1), *i*-Pr_2Zn gave the desired product **11b-*i*-Pr** in poor yield. Then the product **11b-*i*-Pr** was obtained in high yield using *i*-PrMgBr (entry 2). On the other hand, *c*-PrZnBr gave the corresponding product **11b-*c*-Pr** in high yield (entry 3). When *n*-BuMgBr and AllylMgBr were used, the desired products **11b-*n*-Bu** and **11b-Allyl** were obtained in high yields, respectively (entries 4 and 6). On the other hand, bulky *t*-BuMgBr and isopropenyl magnesium bromide did not give the desired product at all (entries 5 and 7). Furthermore, BnMgBr and PhMgBr were available to this reaction (entries 8 and 9). Next, several 3,3-dialkylcyclopropenes were used. When 3,3-diarylcyclopropenes **8c–e** bearing an electron-donating or -withdrawing group on the benzene ring were used, the corresponding products **11c–e** were obtained in high yields (entries 10–12). 3,3-Dialkylcyclopropene **8f** also gave the desired product **11f** in high yield (entry 13). Furthermore, the cyclopropene **8g** bearing diester groups gave the desired product **11g** in good yield (entry 14).

Table 10. Scope of Substrates



Entry	**8**	R^2M	Yield/%
1	**8b**	Et_2Zn	86 (**11b-Et**)
2	**8b**	*i*-Pr_2Zn	81 (**11b-*i*-Pr**)
3	**8b**	*c*-PrZnBr	88 (**11b-*c*-Pr**)
4	**8b**	*n*-BuMgBr	84 (**11b-*n*-Bu**)
5	**8b**	*t*-BuMgBr	nd
6	**8b**	AllylMgBr	85 (**11b-Allyl**)
7	**8b**	isopropenyl-MgBr	nd
8	**8b**	BnMgBr	77 (**11b-Bn**)
9	**8b**	PhMgBr	93 (**11b-Ph**)
10	**8c**	Et_2Zn	73 (**11c**)
11	**8d**	Et_2Zn	82 (**11d**)
12	**8e**	Et_2Zn	98 (**11e**)
13	**8f**	PhMgBr	91 (**11f**)
14	**8g**	Et_2Zn	68 (**11g**)

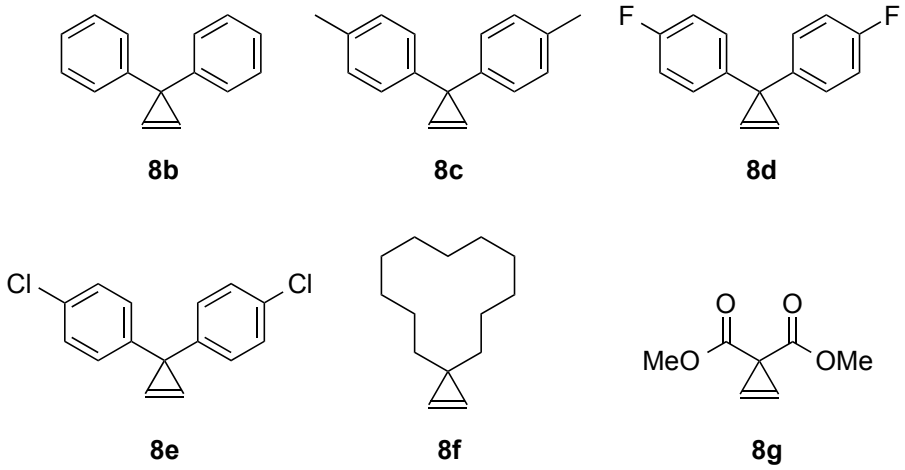
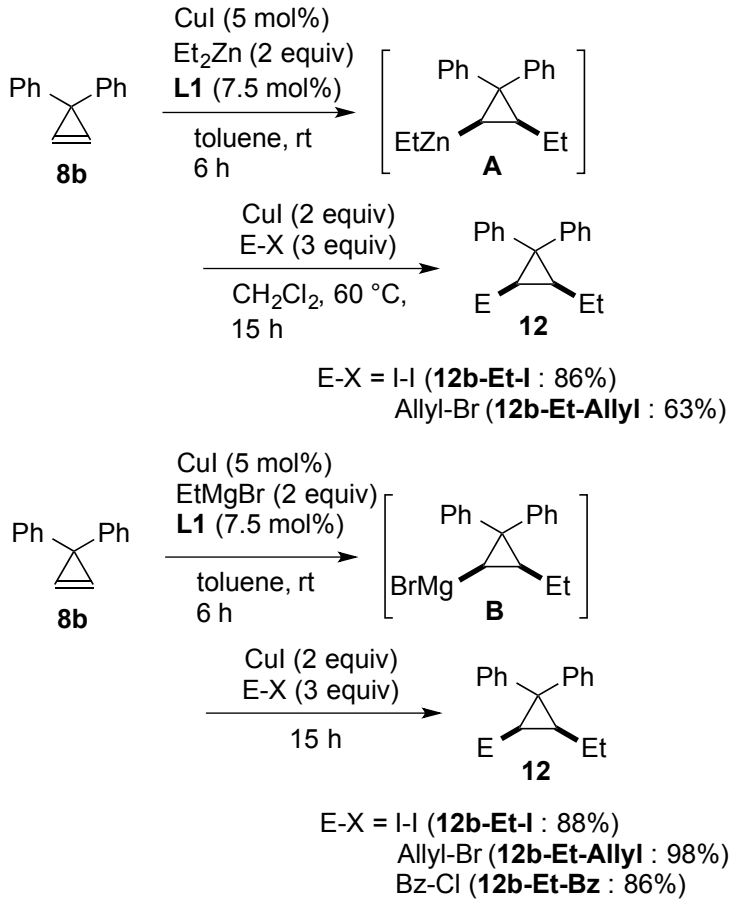


Figure 14. List of Cyclopropenes

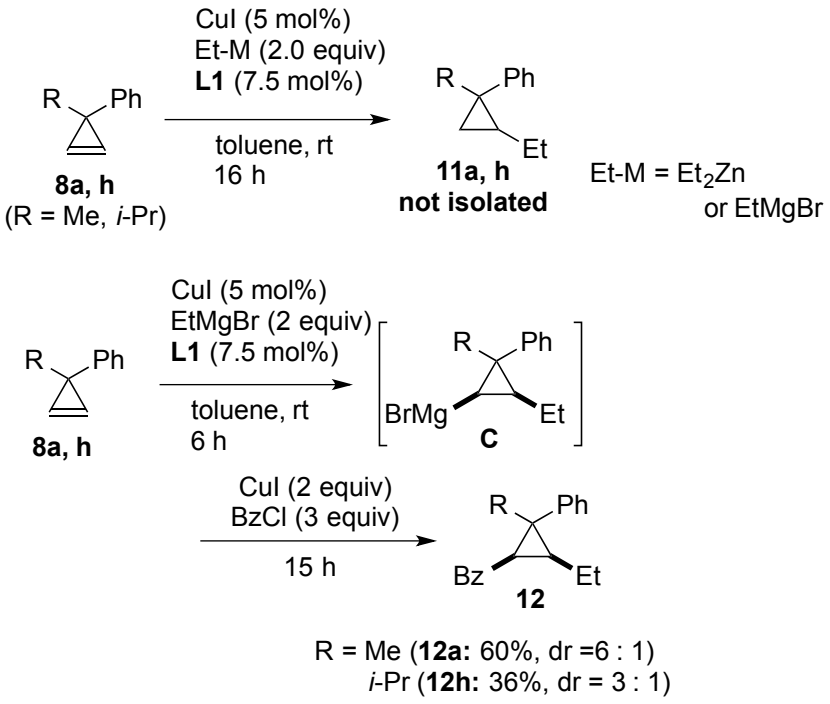
There are some reports for the electrophilic trapping of cyclopropylmagnesium intermediate (Figure 11). In the case of cyclopropylzinc, use of an excess amount of Cu salt allowed the reaction with electrophiles.[31] Therefore, I demonstrated the electrophilic trapping of the cyclopropylzinc intermediate **A** (Scheme 21) to give the multifunctionalized cyclopropanes. The reaction using I_2 or allyl bromide after carbozincation of **8b** gave multifunctionalized cyclopropanes **12b-Et-I** and **12b-Et-Allyl** in moderate to high yield, respectively. When EtMgBr was used instead of Et_2Zn, the electrophilic trapping reaction proceeded to give **12b-Et-I** and **12b-Et-Allyl** in high yields, respectively. Furthermore, **12b-Et-Bz** was obtained in high yield using benzoyl chloride. The nucleophilicity of organomagnesium intermediate is higher than organozinc intermediate. Therefore, when Grignard reagent was used, the trapping reaction proceeded more smoothly.

Scheme 21. Electrophilic Trapping Reaction



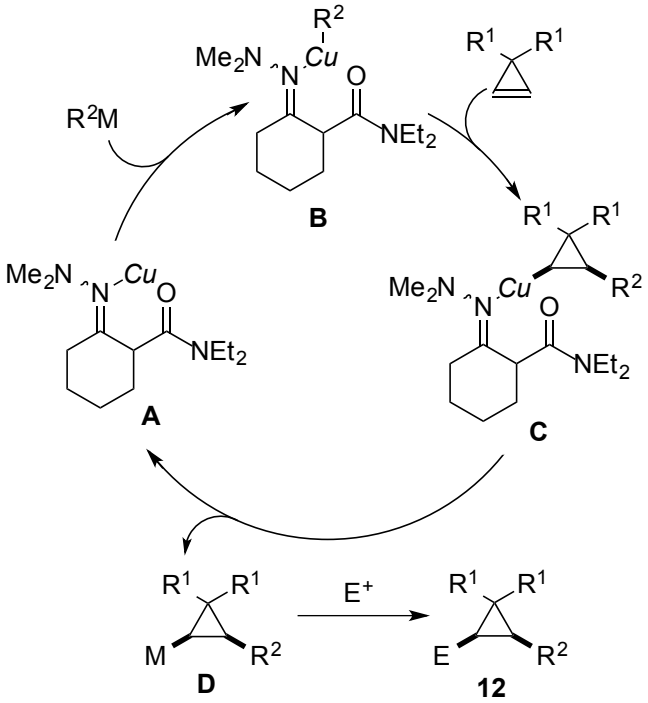
When the 3,3-alkyl, arylcyclopropene **8a** and **8h** were used, the ethyl adducts **11a** and **11h** were also observed by ^{1}H NMR spectrum. However, **11a** and **11f** could not be isolated due to the instability under any conditions (Scheme 22). On the other hand, the desied products **12a** and **12h** were obtained via the electrophilic trapping reaction. These results proved that 3,3-alkyl, arylcyclopropenes are suitable for carbometalation under the conditions of the present reaction. However, when the other electrophiles, such as I_2 and allyl bromide, were used, the corresponding products were not obtained. The benzoyl group might stabilize the cyclopropane products **12a** and **12h**.

Scheme 22. Carbometalation of 3,3-alkyl, arylcyclopropene

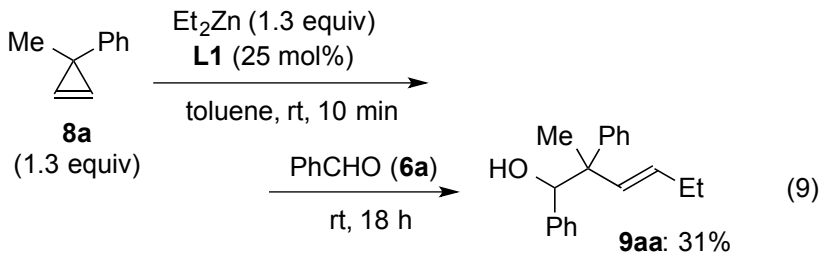


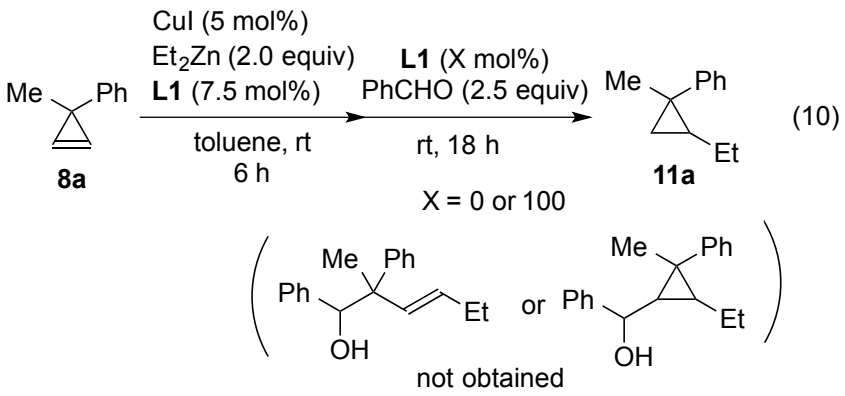
A plausible mechanism for the present reaction is shown in Scheme 23. Generation of cuprate **B** occurred using Cu salt **A** and an excess amount of organometallic reagent in the presence of **L1**. Carbometaltion of cyclopropenes proceeded as a *syn*-fashion to give the cyclopropylmetal intermediate **C**. Furthermore, electrophilic trapping reaction proceeded with retention of stereochemistry. Therefore, the desired product **12** was obtained with *syn*-selectivity.

Scheme 23. Plausible Mechanism



Previously, I showed the allylation of benzaldehyde with allylzinc intermediate derived from dialkylzinc reagents and a cyclopropene (eq. 9). The carbozincation and the subsequent C–C bond cleavage is another possibility for allylzincation. Then, we hypothesized that cyclopropylzinc intermediates generated via the copper-catalyzed carbozincation would take part in the allylzincation of aldehydes in the presence of an appropriate catalyst. However, the desired allylation of benzaldehyde did not proceed and only Et-adduct **11a** was observed on TLC analysis even in the presence of a stoichiometric amount of **L1** (eq. 10). The present result suggests that the ring-opening of cyclopropene might not proceed via the carbozincation of cyclopropenes to generate cyclopropylzinc intermediates.





In summary, I have developed the CuI and hydrazoneamide-catalyzed efficient carbometalation of cyclopropenes. The present carbometalation does not require the functionalized substrates and expensive transition metal catalysts. Various organometallic reagents and cyclopropenes were available to this reaction for the synthesis of multifunctionalized cyclopropanes.[32] The reaction with additional electrophiles after the carbometalation reaction of cyclopropene gave the corresponding multifunctionalized cyclopropanes without a generation of ring-opening product as we reported previously. This result suggested that the tandem allylation reaction did not proceed via carbozincation. Therefore, further studies for generation of carbenoid from cyclopropenes were carried out.

Chapter 4. Ag-catalyzed Ring-Opening of Cyclopropenes

The results in chapter 3 suggested that the tandem allylation reaction includes the generation of zinc carbenoid intermediates, not cyclopropylzinc intermediate. In the past, some metal catalysts, such as Au, Rh and Pd, allowed the generation of carbene intermediates from cyclopropenes as described in introduction chapter. Therefore, the insertion of a carbene intermediate derived from a cyclopropene into a dialkylzinc may occur for the generation of allylzinc intermediates (Figure 15a). In the present reaction, generation of a carbene intermediate is considered as a key step. In the present chapter, screening of other transition metal catalysts to generate carbene intermediates from cyclopropenes was carried out (Figure 15b)

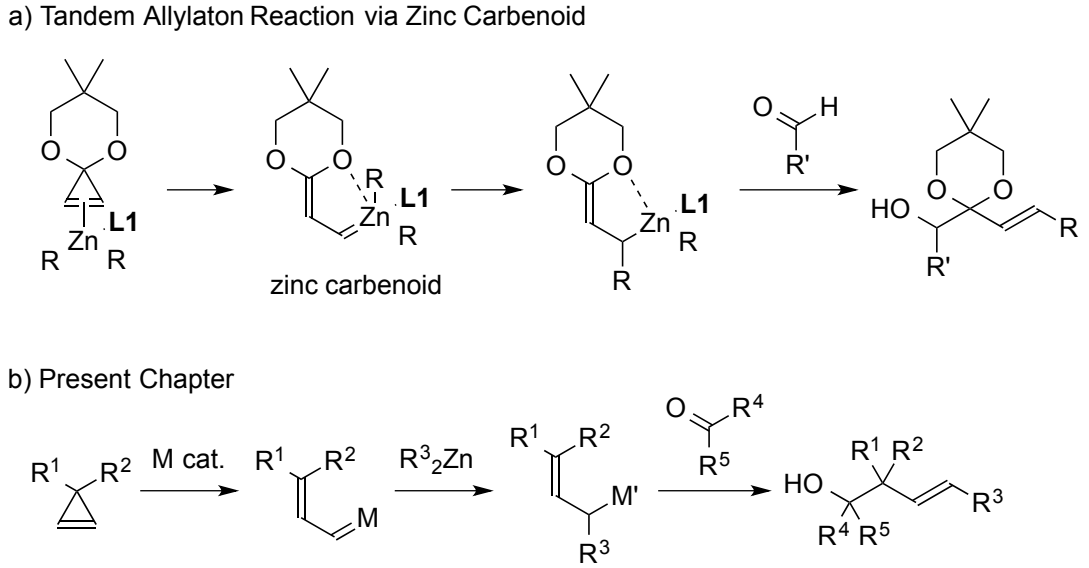


Figure 15. Working hypothesis of the present chapter

In the past, the synthesis of indenes has been reported using cationic Au or Pd catalyst (Figure 16).[33] Furthermore, Dong and co-workers reported the Ag-catalyzed ring-opening of cyclopropene by addition of amines (Figure 17).[34] Therefore, the reaction of aryl cyclopropenes in the presence of a Ag catalyst would give indene derivatives.

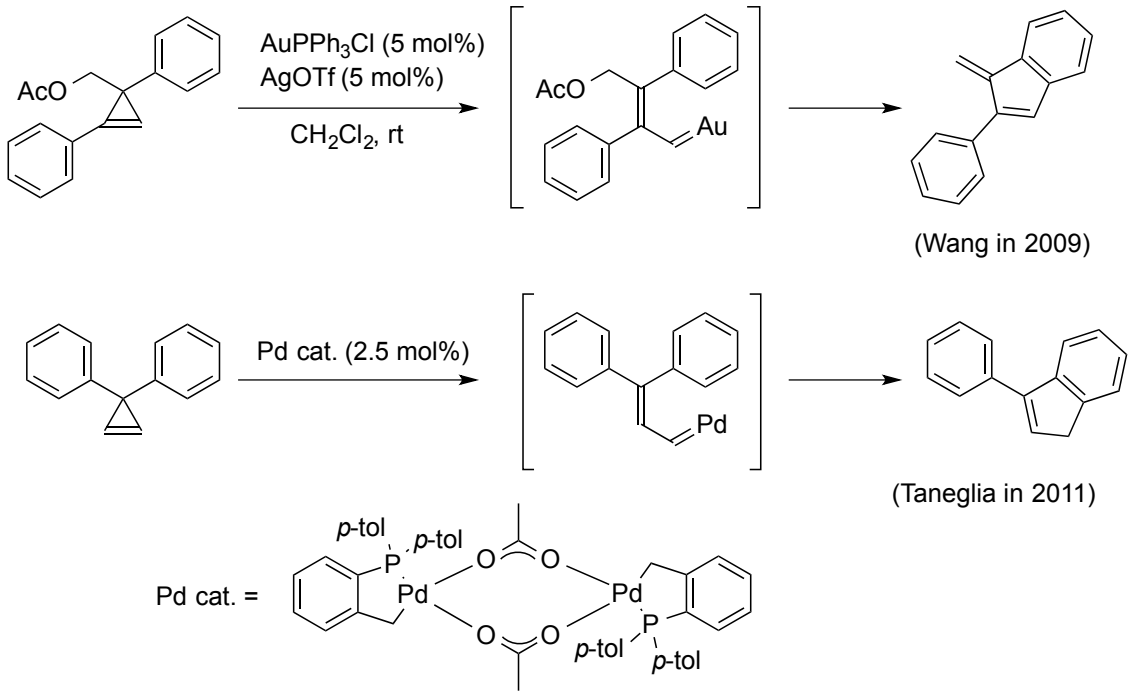


Figure 16. Previous reports of indene synthesis

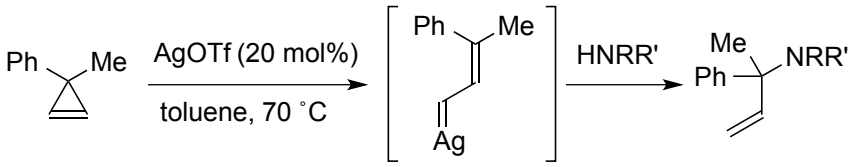
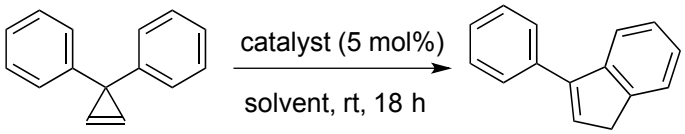


Figure 17. Ring-opening of cyclopropene using Ag catalyst

The examination for the synthesis of indenes using easily available Ag catalyst was carried out (Table 11).[35] Various Ag catalyst, such as AgOTf, AgOAc, $AgNO_3$ and AgF gave the indene product **13b** in high yield (entries 1–4). However, when Ag_2CO_3 was used, product **13b** was obtained in lower yield (entry 5). In the case of Ag_2O, the formation of indene did not proceed (entry 6). Surprisingly, $(Ph_3P)AuCl$ catalyst did not give the desired product at all (entry 7).[36] Other catalysts, such as Zn, Cu, and Rh allowed good results (entries 8–10).[37] Examination of influence by solvent showed that CH_2Cl_2 is the most suitable to the present reaction (entries 11 and 12).

Table 11. Screening of Catalyst for Indene

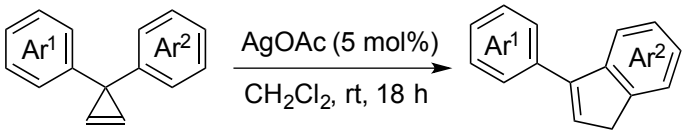


8b **13b**

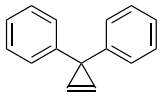
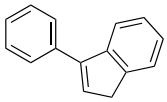
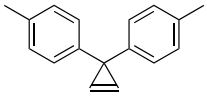
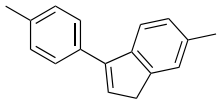
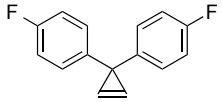
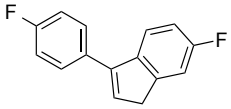
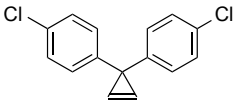
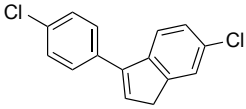
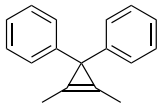
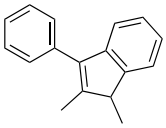
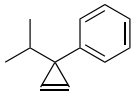
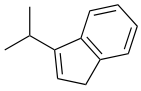
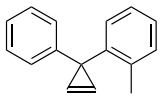
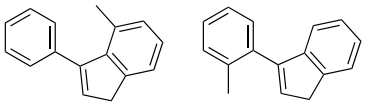
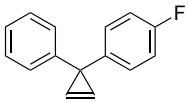
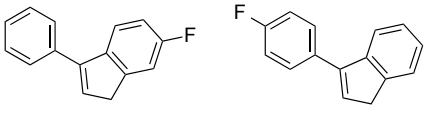
Entry	catalyst	solvent	Yield / %
1	**AgOTf**	**CH_2Cl_2**	**96**
2	**AgOAc**	**CH_2Cl_2**	**95**
3	$AgNO_3$	CH_2Cl_2	92
4	AgF	CH_2Cl_2	93
5	Ag_2CO_3	CH_2Cl_2	15
6	Ag_2O	CH_2Cl_2	nr
7	$AuPPh_3Cl$	CH_2Cl_2	nr
8	ZnI_2	CH_2Cl_2	71
9	CuI	CH_2Cl_2	84
10	$Rh_2(COD)_2Cl_2$	CH_2Cl_2	93
11	AgOTf	toluene	62
12	AgOTf	THF	73

Under the optimized reaction conditions, the scope of cyclopropenes was carried out (Table 12). Various 3,3-diaryl cyclopropenes **8b**, **8c**, **8d** and **8e** gave the indene products **13b**, **13c**, **13d** and **13e** in high yield (entries 1–4). In the present reaction, 1,2-disubstitued cyclopropene **8i** was available (entry 5). When the 3,3-alkyl, aryl cyclopropene **8h** was used, the desired product **13h** was also obtained in good yield (entry 6). The unsymmetrical 3,3-diaryl cyclopropenes **8j** and **8k** gave a mixture of products (entries 7 and 8). In these cases, the selectivity was not observed.

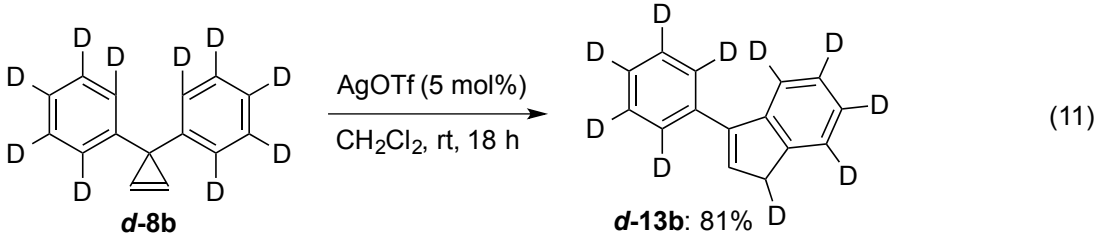
Table 12. Synthesis of Various Indenes



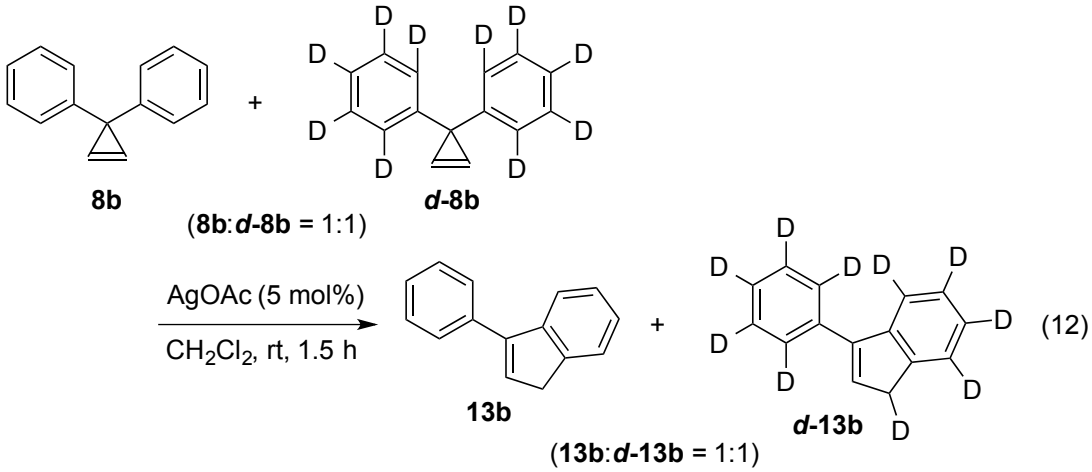
8 **13**

Entry	Substrate	Product
1	 **8b**	 **13b**: 96%
2	 **8c**	 **13c**: 92%
3	 **8d**	 **13d**: 97%
4	 **8e**	 **13e**: 96%
5	 **8i**	 **13i**: 95%
6	 **8h**	 **13h**: 63%
7	 **8j**	 **13j** **13j'** 97% (ratio = 3.2 : 1)
8	 **8k**	 **13k** **13k'** 96% (ratio = 1 : 1)

The synthesis of indenes was carried out using the deuterated cyclopropene to understand the mechanistic details. The indene ***d*-13b** was obtained in good yield from cyclopropene ***d*-8b** (eq. 11).[38] When the mixture of **8b** and ***d*-8b** was used, the mixture of **13b** and ***d*-13b** was obtained in same ratio after the reaction in a half way(eq. 12). These results suggested that the C–H bond cleavage might not be the rate-determining step in the present reaction. Therefore, Friedel-Crafts-type reaction could occur to give the indene product.[39]



(11)

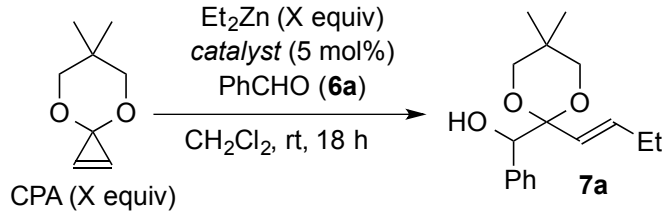


(12)

The indene products would be obtained via vinyl carbenoid from cyclopropenes. The trapping reaction of carbenoid using organometallic reagents could give the allylmetal intermediate for the various homoallylic alcohol derivatives by the addition to carbonyl compounds. Accordingly, the optimization of the allylation reaction was carried out using Ag catalysts (Table 13). CPA was chosen as a model substrate for the present allylation reaction; in our previous report, the allylation reaction proceeded smoothly when CPA was used. When the allylation reaction was performed without catalyst, the desired product **7a** was obtained in low yield as a mixture of unidentified by-products; the Zn-mediated generation of carbenoid intermediate might take place

(entry 1). When AgOTf was used, the product **7a** was obtained in moderate yield (entries 2 and 3). The yield did not increase in the presence of Au catalyst (entries 4 and 5). These results suggested that a Ag catalyst is essential for the present allylation reaction. Therefore, screening of the Ag catalysts was carried out (entries 6–11). As a result, AgOAc gave the desired product **7a** in 54% yield. When the amount of CPA and Et_2Zn was increased to 3 equivalent, **7a** was obtained in 91% yield (entry 8). On the other hand, ZnI_2 showed a low activity in compared with Ag catalyst (entries 12 and 13).

Table 13. Optimization of Reaction Conditions

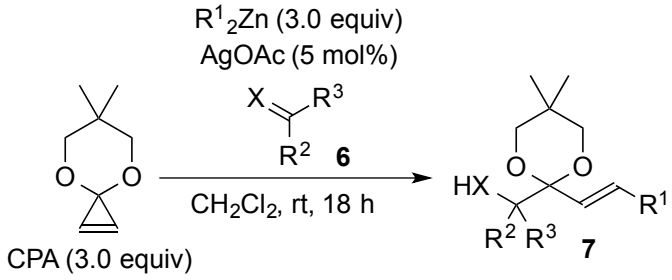


Entry	X / equiv	*catalyst*	Yield / %
1	1.1	-	< 24
2	1.1	AgOTf (5 mol%)	40
3[a]	1.1	AgOTf (5 mol%)	31
4	1.1	$Au(PPh_3)Cl$ (5 mol%) + AgOTf (5 mol%)	43
5	1.1	$Au(PPh_3)Cl$ (5 mol%)	35
6	1.1	AgOAc (5 mol%)	54
7	2.0	AgOAc (5 mol%)	74
8	**3.0**	**AgOAc (5 mol%)**	**91**
9	1.1	Ag_2CO_3 (5 mol%)	51
10	1.1	$AgNO_3$ (5 mol%)	33
11	1.1	$AgSbF_6$ (5 mol%)	nd
12	1.1	ZnI_2 (20 mol%)	22
13	1.1	ZnI_2 (100 mol%)	38

[a] Toluene was used as a solvent.

Under the optimized reaction conditions, the scope of carbonyl compounds was carried out using CPA (Table 14). As a result, the desired homoallylic alcohols **7** were obtained in higher yields than result of chapter 2 (Table 8), respectively (entries 1–14). When the aldimine **6o** was used as an electrophile, the corresponding homoallylic amine **7o** was obtained in good yield (entry 15). The ketone **6p** also gave the desired product **7p** in moderate yield (entry 16).

Table 14. Allylation Reaction via Ring-Opening of CPA

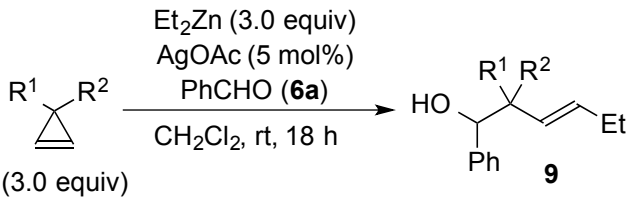


Entry	R^1	R^2, R^3, X	Yield / %
1	Et	Ph, H, O (**6a**)	91 (**7a**)
2	Me	Ph, H, O (**6a**)	64 (**7a-Me**)
3	*i*-Pr	Ph, H, O (**6a**)	59 (**7a-*i*-Pr**)
4	Et	2-MeC_6H_4, H, O (**6b**)	68 (**7b**)
5	Et	3-MeC_6H_4, H, O (**6c**)	83 (**7c**)
6	Et	4-MeC_6H_4, H, O (**6d**)	95 (**7d**)
7	Et	4-$MeOC_6H_4$, H, O (**6f**)	94 (**7f**)
8	Et	4-FC_6H_4, H, O (**6g**)	83 (**7g**)
9	Et	1-naphthyl, H, O (**6h**)	84 (**7h**)
10	Et	2-furyl, H, O (**6j**)	92 (**7j**)
11	Et	2-Phenylethyl, H, O (**6k**)	71 (**7k**)
12	Et	2-Phenylethenyl, H, O (**6l**)	72 (**7l**)
13	Et	*c*-Hex, H, O (**6m**)	86 (**7m**)
14	Et	*t*-Bu, H, O (**6n**)	46 (**7n**)[a]
15	Et	Ph, H, NTs (**6o**)	78 (**7o**)
16	Et	Ph, CF_3, O (**6p**)	43 (**7p**)

[a] The product was isolated as a ketone after deprotection of acetal moiety.

The allylation reaction occurred using 3,3-dialkyl cyclopropenes instead of CPA; the previous conditions gave pity results as described in chapter 2 (Table 15). The 3,3-phenyl methyl cyclopropene **8a** gave the homoallylic alcohol **9aa** in 77% yield as a diastereomeric mixture (entry 1). Although the 3,3-phenyl ethyl cyclopropene **8l** also gave the desired product **9la**, 3,3-phenyl isopropyl cyclopropene **8h** did not give the corresponding product **9ha** (entries 2 and 3). The cyclopropene **8m** bearing 1-naphthyl group gave the product **9ma** in lower yield due to the steric hindrance (entry 4). 3,3-Diphenyl cyclopropene **8b** also gave the product **9ba** in good yield (entry 5); however, cyclopropene **8c** was not available (entry 6). Although the cyclopropene **8d** and **8e** were available, the desired products were obtained in lower yield (entries 7 and 8). When the cyclopropenes **8d** and **8e** were used, the generation of carbene intermediate might be inhibited by an electron-withdrawing group. In the case of cyclopropene **8g**, the corresponding product was not obtained at all (entry 9). The use of Ag catalyst allowed the various multifunctionalized allylmetal reagents from cyclopropenes.

Table 15. Scope of Cyclopropenes



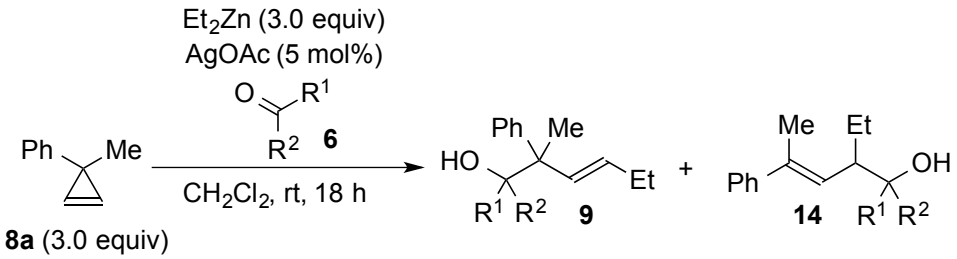
Entry	R^1, R^2	Yield / %
1	Ph, Me (**8a**)	77 (**9aa**) [a]
2	Ph, Et (**8l**)	63 (**9la**) [b]
3	Ph, *i*-Pr (**8h**)	trace
4	1-Naph, Me (**8m**)	32 (**9ma**) [c]
5	Ph (**8b**)	56 (**9ba**)
6	4-MeC_6H_4 (**8c**)	nd[d]
7	4-FC_6H_4 (**8d**)	33 (**9da**)
8	4-ClC_6H_4 (**8e**)	48 (**9ea**)
9	CO_2Et (**8g**)	nd

[a] dr = 1.6 : 1. [b] dr = 4 : 1. [c] dr = 5 : 3.

[d] Indene product **2b** was observed.

Furthermore, when the cyclopropene **8a** was used, various ketones were available for the tandem allylation reaction (Table 16). The ketones **6q**, **6r**, **6p**, **6s**, and **6t** gave the homoallylic alcohols **9aq**, **9ar**, **9ap**, **9as**, and **9at** in good yields (entries 1-5). The dioxanone **6u** was available in the present reaction to give the densely functionalized product **9au** (entry 6). When 3-pentanone **6v** was used, the mixture of **9av** and regioisomer **14av** was obtained (entry 7). Furthermore, the bulky ketones **6w**, **6x**, and **6y** gave the products **14aw**, **14ax**, and **14ay** selectively (entries 8–10).

Table 16. Scope of Ketones



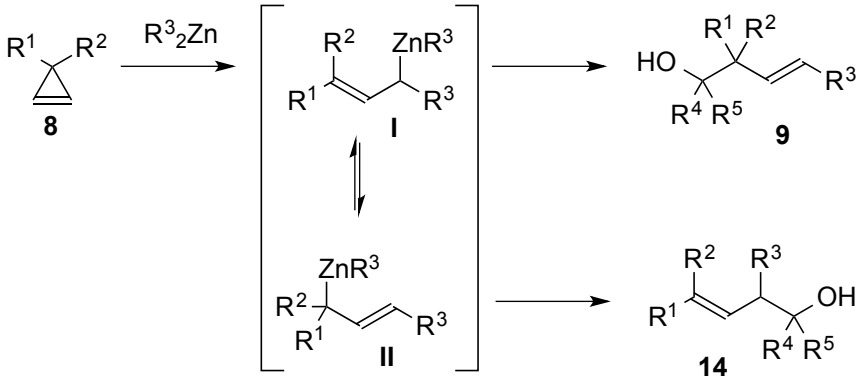
Entry	R^1, R^2	Product
1	Me (**6q**)	67 (**9aq**)
2	Ph, Me (**6r**)	83 (**9ar**)[a]
3	Ph, CF_3 (**6p**)	51 (**9ap**)[b]
4	$(CH_2)_4$ (**6s**)	86 (**9as**)
5	$(CH_2)_5$ (**6t**)	88 (**9at**)
6	$CH_2OC(CH_3)_2OCH_2$ (**6u**)	78 (**9au**)
7	Et (**6v**)	38 (**9av**), 21 (**14av**)
8	Ph (**6w**)	55 (**14aw**)
9	Bn (**6x**)	58 (**14ax**)
10	*c*-Pr (**6y**)	27 (**14ay**)

[a] dr = 2 : 1 [b] dr = 10 : 9

The generation of products **14** suggested that the present reaction includes the isomerization of the allylzinc intermediate (Scheme 24).[40] Namely, the allylzinc intermediates **I** derived from cyclopropenes **8** could add to the ketones to give the products **9**. However, when the bulky ketones were used, the steric hindrance could inhibit the nucleophilic attack of the tertiary carboanion to ketones. Therefore, the addition of isomerized allylzinc intermediate **II** to ketones gave the regioisomers **14**.

The products **14** were obtained as a single isomer. The stereochemistry of olefin moiety of **14** was determined by NOESY study. The NOESY study of **14aw** showed the interaction of methyl substituent and H^a (Figure 18). Both of products **9** and **14** were obtained with *E*-selectivity. Namely the allylzinc intermediates **I** and **II** take part in the generation of the more stable **TS-I** and **TS-III** to give the several products (scheme 25). The six-membered transition states bearing the bulky substituentat the axial positions are unfavorable conformation due to steric hindrance (**TS-II** and **TS-IV**)

Scheme 24. Generation of the Regioisomer 14



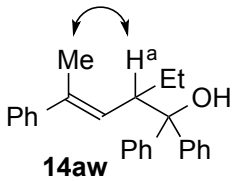
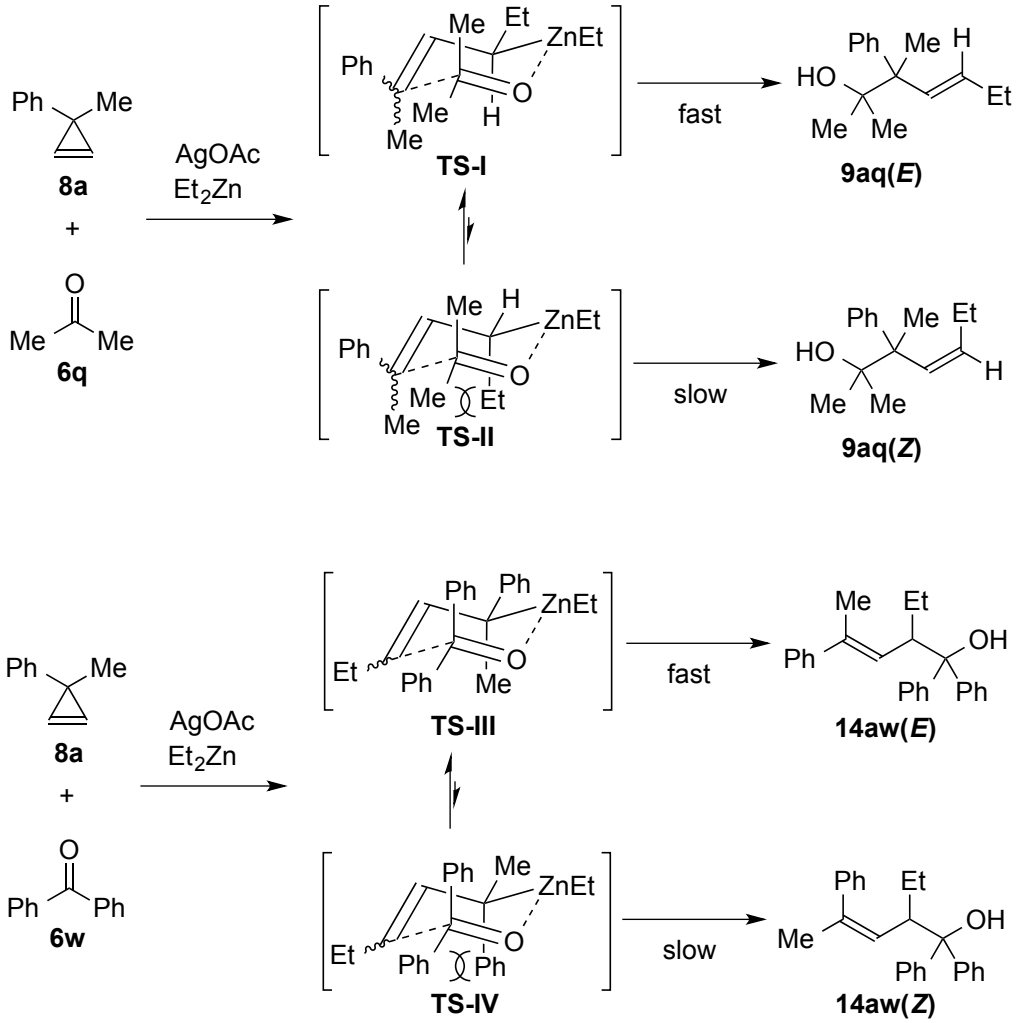


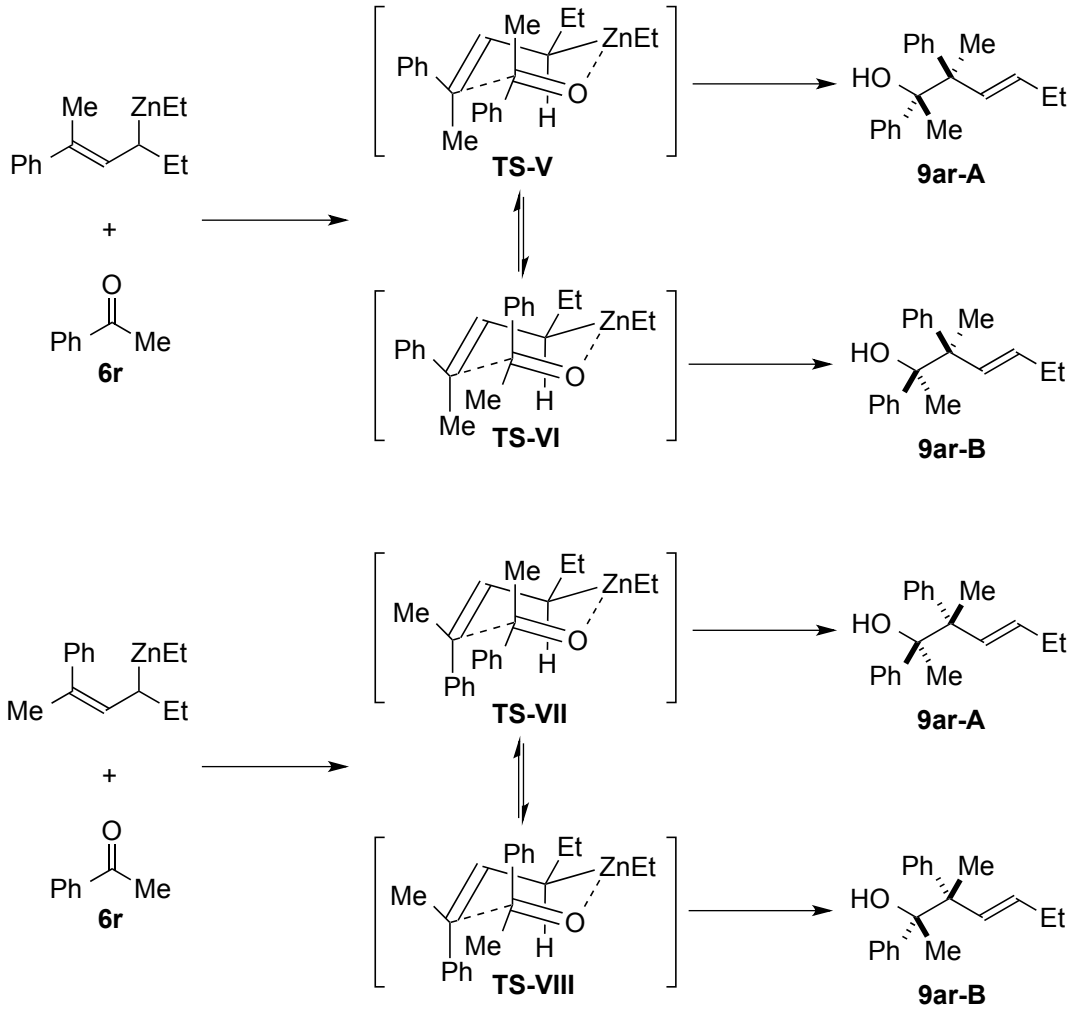
Figure 18. NOESY Study for Determination of the Stereochemistry of the Olefin

Scheme 25. *E*-Selectivity of Products



When the unsymmetrical ketone, such as acaetophenone **6r**, was used, the product **9ar** was obtained as a diastereomeric mixture as shown in table 16. In this case, the allylation reaction might proceed via **TS-V**, **VI**, **VII**, and **VIII** in scheme 26. The diastereomeric mixture **9ar-A** and **9ar-B** was obtained because of the stereochemistry of allylzinc intermediate and conformation of ketone were not definite.

Scheme 26. Transition States of Allylation Reaction to Give the Product 9



When CPA was used, acetophenone **6r** gave the product **10r** in low yield. The corresponding product **10r** was difficult to separate from the unreacted acetophenone. Therefore, the desired product was isolated as a ketone **10r** after the deprotection of acetal moiety (eq. 13). The present result suggested that coordination of the acetal moiety on a Zn-center might stabilize the allylzinc intermediate. Therefore, the allylzinc intermediate derived from **8a** showed the higher reactivity (Figure 19).

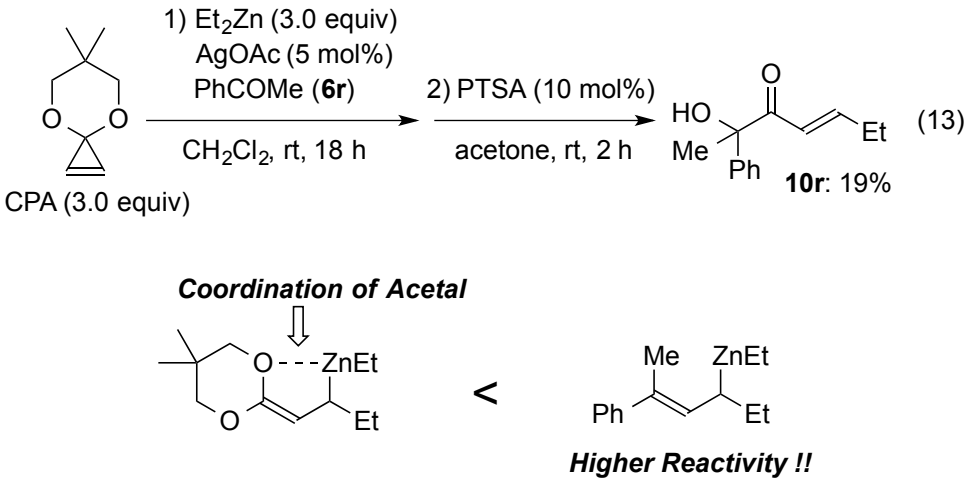
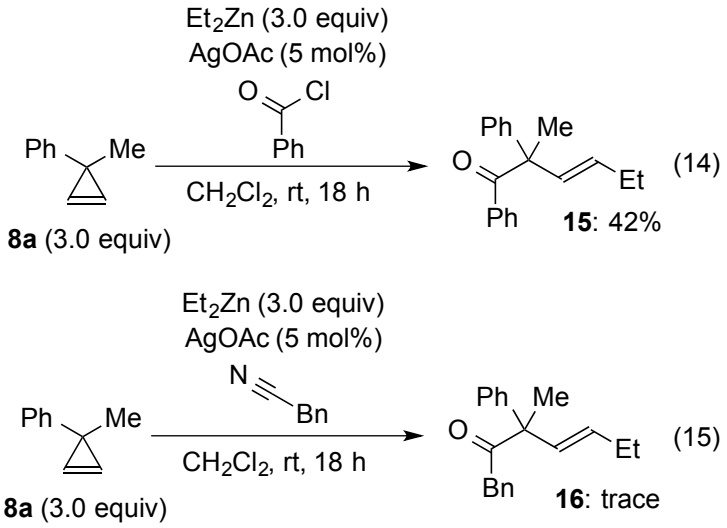


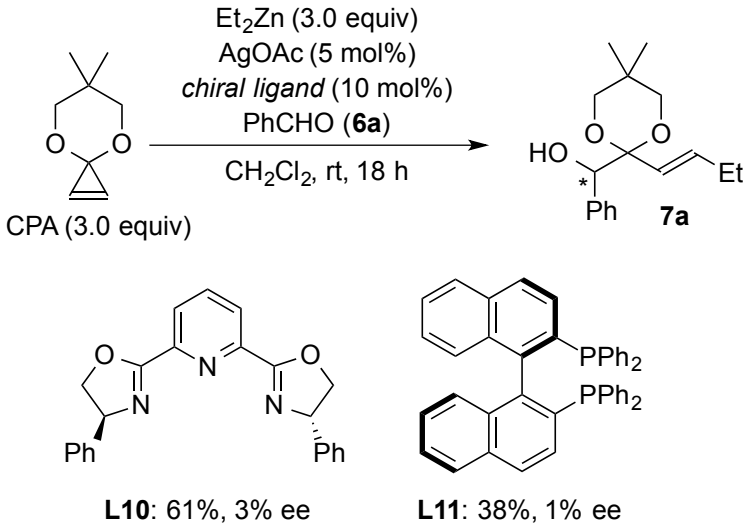
Figure 19. Reactivity of Allylzinc Intermediate

The allylation reaction using benzoylchloride as an electrophile gave the ketone product **15** in moderate yield (eq. 14). As a side reaction, Et_2Zn and benzoylchloride gave the propionphenone in the presence of AgOAc.[41] Therefore, the yield was not increased anymore. On the other hand, when phenylacetonitrile was used, a trace amount of the ketone product **16** was observed and could not be isolated (eq. 15). Any other nitrile compounds did not give the ketone products at all. The electrophilicity of nitrile group would be insufficient for the present reaction.



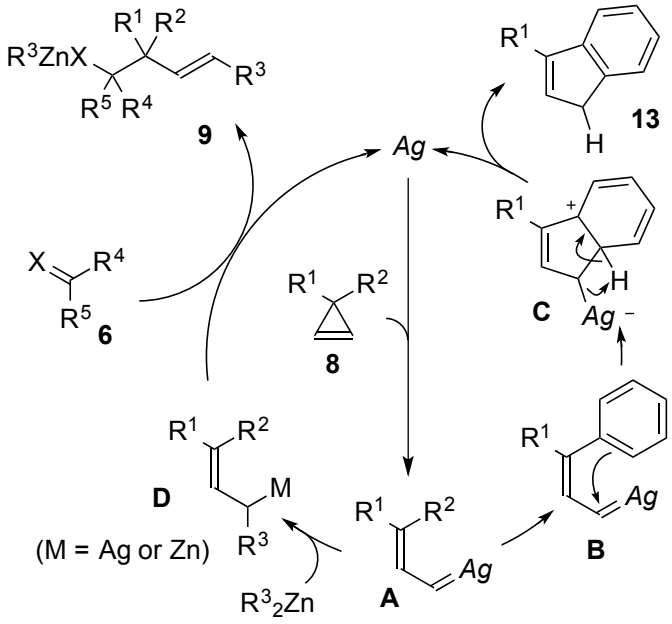
I examined the asymmetric allylation reaction using chiral ligand (Scheme 27). When **L10** was used as a ligand, the desired product was obtained in good yield, however, the enantioselectivity was poor. In the past, the BINAP (**L11**) was used as a chiral ligand for Ag center [42]. However, BINAP is not suitable for the present reaction.

Scheme 27. Tandem Allylation Reaction with Chiral Ligand



A proposed mechanism for the present reaction is shown in Scheme 28. The vinylcarbenoid **A** was generated from cyclopropene **8** in the presence of a Ag catalyst. When AgOTf was used, the Friedel-Crafts-type reaction occurred to give the indene product **13** via the intermediate **B** and **C**. In the allylation reaction, allylmetal intermediate **D** was generated with organozinc reagent. The allylation reaction of carbonyl compounds **6** proceeded to give the desired product **9**.

Scheme 28. Proposed Mechanism



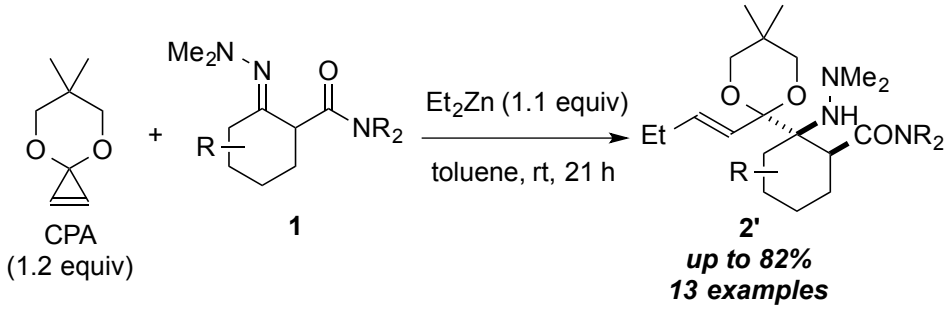
In conclusion, we have developed the Ag-catalyzed tandem allylation reaction and Friedel-Crafts-type reaction for the synthesis of indenes. These reactions involve the generation of the vinyl carbenoid from cyclopropenes in the presence of a Ag catalyst. Addition of organozinc reagents gave allylmetal intermediates to give the homoallylic alcohols via allylation reaction. When the Friedel-Crafts-type reaction proceeded, the indene derivatives were obtained.

Summary

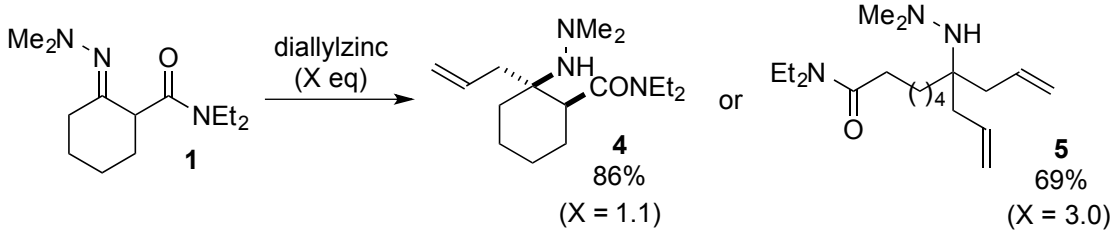
In the present paper, the tandem allylation reaction via ring-opening of cyclopropenes was reported. The present reaction includes the generation of multi-functionalized allylmetal intermediate to give the various homoallylic alcohol derivatives, which are widely used for synthetic intermediate toward natural products.

Chapter 1

The tandem allylation reaction using allylzinc intermediates from cyclopropenes was achieved. The cyclopropenone acetal (CPA) was used as a substrate for the generation of vinylcarbene intermediates due to the stabilization by the coordination of an acetal moiety on a Zn center. Furthermore, the allylzinc intermediate from CPA acts as a novel acylanion equivalent to add the cyclic β-hydrazoneamide **1**. The present reaction gave the sterically congested hydrazine products **2** as a single diastereomer.

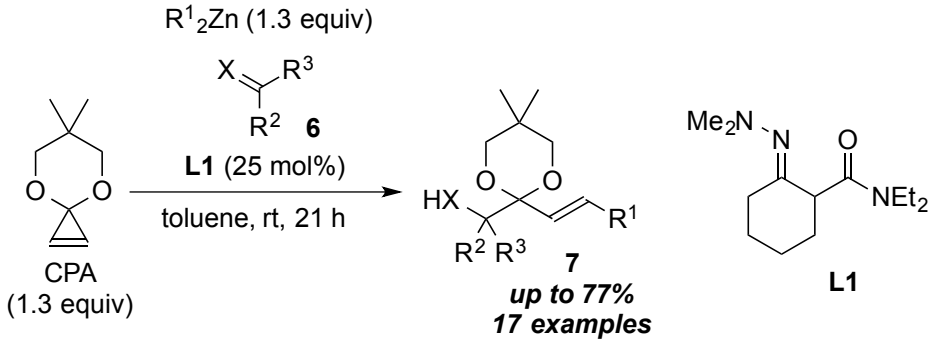


In chapter 1, the allylation reaction of β-hydrazoneamides **1** with diallylzinc was also reported. The diallylzinc was activated by coordinative substrates to add the unactivated carbonyl derivatives smoothlyto give the product **4**. When an excess amount of diallylzinc was used, the diallylation of hydrazone proceeded via cleavage of amide moiety like a retro-Manich reaction to give the product **5**.



Chapter 2

The allylzinc intermediate allowed the addition to the external electrophiles **6**; aldehydes, an aldimine and a ketone. In the present reaction, the β-hydrazoneamide **L1** acts as a ligand to promote the generation of allylzinc intermediate. As a result, a wide variety of functionalized homoallyllic alcohols or amine **7** were obtained in a one-pot procedure.



Chapter 3

The Cu-catalyzed carbometalation of unfunctionalized cyclopropenes **8** was described. Chapter 1 and 2 describes the tandem allylation reaction proceeded via carbene intermediate as a working hypothesis. However, there is another possibility; the initial step of the allylation reaction was carbozincation of cyclopropenes. Therefore, the generation of cyclopropylzinc intermediates was examined via carbozincation of various cyclopropenes for the subsequent ring-opening to give allylzinc intermediates. As a result, the various cyclopropane products **11** were obtained in high yields.

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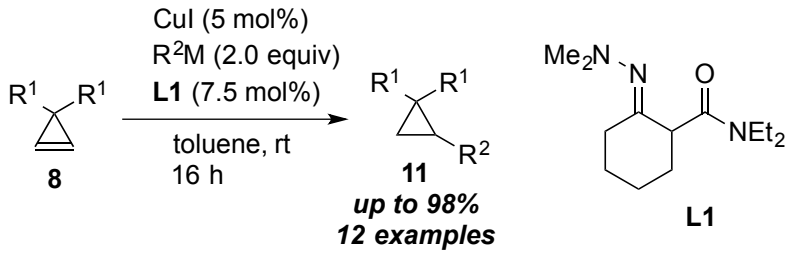
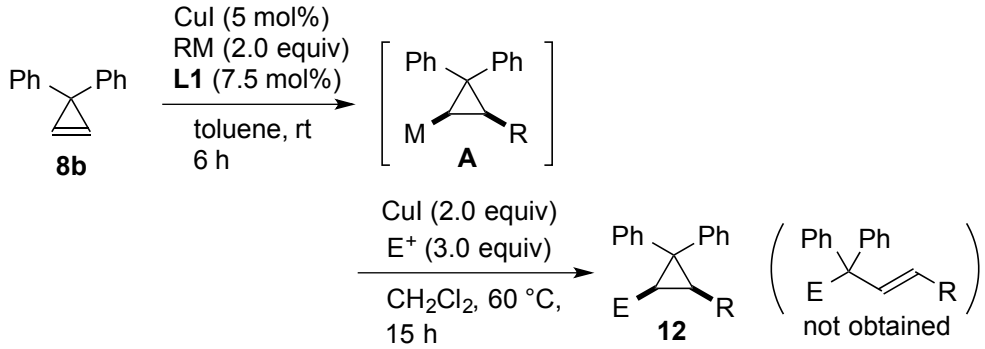
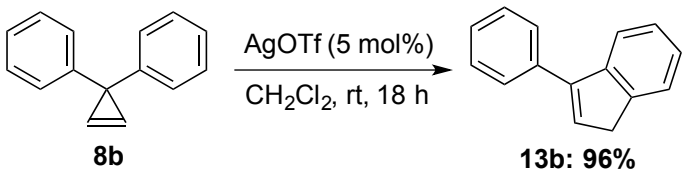


Furthermore, the electrophilic trapping of the cyclopropylzinc intermediate **A** was demonstrated. The trapping reaction gave the mutifunctionalized cyclopropanes **12**, however, the allylation reaction via ring-opening of cyclopropylzinc did not occur. The present result suggests that the ring-opening of cyclopropene might not proceed via the carbozincation of cyclopropenes to generate cyclopropylzinc intermediates.

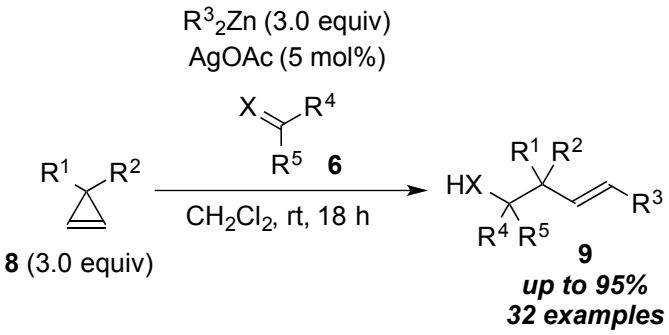


Chapter 4

Silver-catalyzed ring-opening of cyclopropenes via carbene intermediates was achieved. As a result of screening of metal catalyst, AgOTf gave the indene product **13b** in high yield via vinylcarbenoid from cyclopropene **8b**.



The generation of allylmetal intermediate by the trapping reaction of siliver carbene intermediate using organometallic reagent was investigated. In the present reaction, the use of dialkylzinc reagent and AgOAc allowed the multifunctinalized allylzinc intermediates from cyclopropenes **8**. The various homoallylic alcohol derivatives **9** were obtained via allylation reaction of carbonyl derivatives **6**.

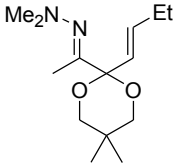


Experimental Section

General: ^{1}H NMR spectra were recorded on a JEOL ECS 400 (400 MHz) NMR spectrometer. Chemical shifts δ are reported in parts per million (ppm) using tetramethylsilane (TMS) as an internal standard. Data are reported as follows: Chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad), coupling constant (*J*) and integration. ^{13}C NMR spectra were recorded on a JEOL ECS 400 (100 MHz) NMR spectrometer. The chemical shifts were determined in the δ-scale relative to $CDCl_3$ (δ = 77.0 ppm). The IR spectra were measured on JASCO FT/IR−230 and JASCO IR A−1 spectrometers. The MS spectra were recorded with Hitachi M−80 and JEOL SX−102A mass spectrometers. Melting points were measured with an AS ONE melting points apparatus (ATM−01) and the values are reported on the centigrade temperature scale (°C). Toluene was dried and distilled over sodium. THF and Et_2O were freshly distilled from sodium diphenylketyl. All other solvents were distilled and stored over drying agents. All anhydrous solvents used in the present experiments were degassed by freeze−thaw (3 cycles) prior to use. Thin−layer chromatography (TLC) and flash column chromatography were performed by using Merck silica gel 60 PF_{254} (Art. 7749) and Cica−Merck silica gel 60 (No. 9385−5B), respectively.

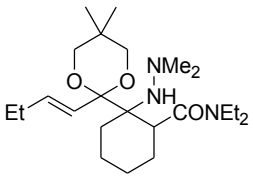
Chapter 1

General Method: To a solution of compound **1** (0.3mmol) in toluene (1.5 ml), Et_2Zn (0.33 mmol, 1.0 M in toluene) was added at room temperature. After stirring for 2 h, CPA (50 mg, 0.36 mmol) was added at room temperature and stirred for 21 h. Reaction mixture was quenched with a sat. NH_4Cl. The aqueous layer was separated and extracted with AcOEt and dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane / AcOEt = 3 / 1).

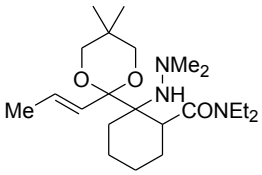


(*E*)-2-(1-(2-((*E*)-but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)ethylidene)-1,1-dimethylhydrazine (**2d**); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.74 (s, 3H), 0.92 (t, *J* = 7.4

Hz, 3H), 1.07 (s, 3H), 1.84 (s, 3H), 2.01 (m, 2H), 2.47 (s, 6H), 3.47 (m, 4H), 5.35 (d, *J* = 15.6 Hz, 1H), 5.88 (dt, *J* = 6.4, 15.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 22.3, 22.8, 25.0, 29.7, 46.9, 71.8, 99.0, 127.7, 135.4, 163.7; IR (neat, cm^{-1}) 2955, 2870, 1734, 1653, 1470, 1394, 1361, 1238, 1184, 1088, 1012, 979, 944, 795, 669; HRMS (EI) *m/z* calcd. for $C_{14}H_{26}N_2O_2$ 254.20 [M^+]; found: 254.1995.

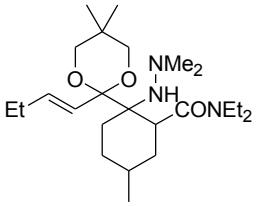


(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclohexanecarboxamide (**2'f**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.56 (s, 3H), 0.99 (m, 6H), 1.07 (s, 3H), 1.11 (t, *J* = 7.3 Hz, 3H), 1.23 (m, 2H), 1.46 (m, 2H), 1.65 (m, 2H), 2.03 (m, 2H), 2.35 (m, 2H), 2.44 (s, 6H), 2.82 (d, *J* = 12.4 Hz, 1H), 2.96 (m, 1H), 3.09 (m, 1H), 3.21 (m, 2H), 3.39-3.64 (m, 4H), 4.21 (br, 1H), 5.00 (d, *J* = 16.4 Hz, 1H), 5.57 (dt, *J* = 6.4, 16.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 14.5, 22.2, 22.5, 23.6, 25.5, 26.1, 27.8, 28.5, 30.0, 40.5, 41.8, 42.5, 50.8, 67.2, 70.1, 71.2, 103.8, 124.8, 138.5, 176.2; IR (neat, cm^{-1}) 3305, 2936, 2801, 2758, 1714, 1626, 1455, 1379, 1265, 1245, 1220, 1119, 1073, 1038, 986, 847, 915, 865, 839, 791, 732; HRMS (EI) *m/z* calcd. for $C_{23}H_{43}N_3O_3$ 409.33 [M^+]; found: 409.3306.

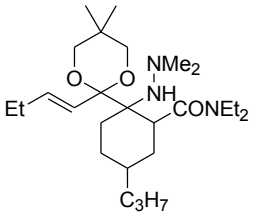


(*E*)-2-(5,5-dimethyl-2-(prop-1-enyl)-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclohexanecarboxamide (**2'f-Me**); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 3H), 1.08 (t, *J* = 6.9 Hz, 3H), 1.14 (s, 3H), 1.18 (t, *J* = 7.3 Hz, 3H), 1.30-1.33 (m, 1H), 1.51-1.57 (m, 1H), 1.68-1.75 (m, 7H), 2.42-2.46 (m, 1H), 2.52 (s, 6H), 2.87 (d, *J* = 12.4 Hz, 1H), 2.99-3.18 (m, 2H), 3.23-3.33 (m, 2H), 3.42-3.66 (m, 4H), 4.25 (br, 1H), 5.10 (d, *J* = 16.0 Hz, 1H), 5.57 (dt, *J* = 6.4, 16.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 14.6, 17.9, 22.2, 22.4, 23.6, 26.1, 27.7, 28.5, 30.1, 40.6, 41.7, 42.4, 50.9, 67.2, 70.1, 71.4, 76.6, 77.0, 77.3, 103.6, 127.2, 131.7, 176.1; IR (neat, cm^{-1}) 3299, 2936,

2857, 2803, 2760, 2238, 1633, 1447, 1395, 1378, 1362, 1278, 1245, 1220, 1134, 1103, 1068, 1037, 1009, 987, 947, 926, 730; HRMS (EI) *m/z* calcd. for $C_{22}H_{41}N_3O_3$ 395.3148 [M^+]; found: 395.3147.

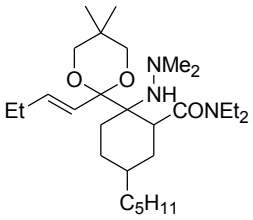


(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-5-methylcyclohexanecarboxamide (**2'j**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 3H), 0.89 (d, *J* = 5.9 Hz, 3H), 1.05 (m, 6H), 1.14 (s, 3H), 1.18 (t, *J* = 6.7 Hz, 3H), 1.39-1.59 (m, 4H), 1.80 (q, *J* = 12.4 Hz, 1H), 2.09 (m, 2H), 2.39-2.51 (m, 7H), 2.92-3.04 (m, 2H), 3.16 (m, 1H), 3.28 (m, 2H), 3.54 (m, 2H), 3.66 (m, 2H), 4.27 (br, 1H), 5.05 (d, *J* = 16.5 Hz, 1H), 5.63 (dt, *J* = 6.9, 16.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 14.6, 22.5, 23.6, 25.5, 27.9, 30.1, 31.0, 32.4, 36.7, 40.6, 41.6, 42.5, 50.9, 66.8, 70.1, 71.2, 103.7, 124.8, 138.5, 176.0; IR (neat, cm^{-1}) 3300, 2950, 2869, 2803, 2761, 2237, 1633, 1455, 1362, 1315, 1269, 1118, 1072, 925, 858, 790, 731; HRMS (EI) *m/z* calcd. for $C_{24}H_{45}N_3O_3$ 423.35 [M^+]; found: 423.3459.

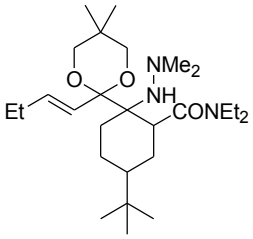


(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-5-propylcyclohexanecarboxamide (**2'k**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 3H), 0.86 (t, *J* = 7.3 Hz, 3H), 1.05 (m, 6H), 1.13-1.21 (m, 8H), 1.25-1.37 (m, 5H), 1.57 (m, 2H), 1.79 (q, *J* = 12.4 Hz, 1H), 2.44-2.50 (m, 7H), 2.93 (d, *J* = 12.4 Hz, 1H), 3.00-3.18 (m, 2H), 3.28 (m, 2H), 3.46-3.71 (m, 4H), 4.26 (br, 1H), 5.05 (d, *J* = 16.5 Hz, 1H), 5.63 (dt, *J* = 6.9, 16.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 14.3, 14.6, 19.9, 22.5, 23.6, 25.5, 27.9, 28.9, 30.1, 34.8, 37.1, 39.3, 40.6, 41.6, 42.5, 51.0, 67.2, 70.1, 71.2, 103.7, 124.8, 138.5, 176.1; IR (neat, cm^{-1}) 3736, 2954, 2869, 1636, 1457, 1377, 1247, 1122, 1075, 1008, 747; HRMS (EI) *m/z* calcd. for

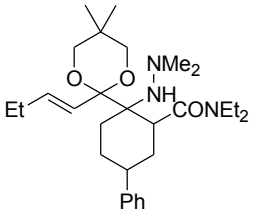
$C_{26}H_{49}N_3O_3$ 451.38 [M^+]; found: 451.3779.



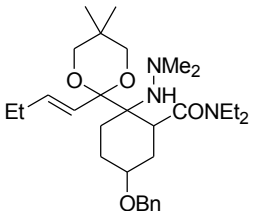
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-5-pentylcyclohexanecarboxamide (**2'l**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 3H), 0.86 (t, *J* = 7.3 Hz, 3H), 1.05 (m, 6H), 1.13-1.40 (m, 18H), 1.56 (m, 2H), 1.78 (q, *J* = 12.8 Hz, 1H), 2.09 (m, 2H), 2.39-2.50 (m, 7H), 2.93 (d, *J* = 12.8 Hz, 1H), 3.00-3.18 (m, 2H), 3.28 (m, 2H), 3.43-3.70 (m, 4H), 4.26 (br, 1H), 5.05 (d, *J* = 16 Hz, 1H), 5.63 (dt, *J* = 6.4, 16 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.6, 14.1, 14.6, 22.5, 22.6, 23.6, 25.6, 26.4, 27.9, 28.9, 30.1, 32.1, 34.9, 37.0, 37.3, 40.6, 41.6, 42.5, 50.8, 67.2, 70.1, 71.2, 103.7, 124.8, 138.5, 176.1; IR (neat, cm^{-1}) 2930, 2854, 2802, 2760, 1636, 1455, 1395, 1361, 1260, 1220, 1127, 1073, 1006, 907, 790; HRMS (EI) *m/z* calcd. for $C_{28}H_{53}N_3O_3$ 479.41 [M^+]; found: 479.4082.



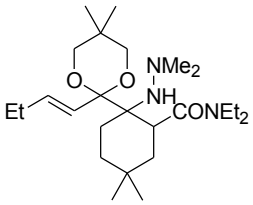
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-5-(tert-butyl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclohexanecarboxamide (**2'm**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.56 (s, 3H), 0.78 (s, 9H), 1.00 (m, 6H), 1.06-1.12 (m, 7H), 1.25 (m, 1H), 1.49 (m, 3H), 1.80 (q, *J* = 12.4 Hz, 1H), 2.03 (m, 2H), 2.35-2.44 (m, 7H), 2.83 (d, *J* = 12.4 Hz, 1H), 3.05 (m, 2H), 3.20 (m, 2H), 3.37 (m, 1H), 3.51-3.64 (m, 3H), 4.15 (br, 1H), 4.96 (d, *J* = 16 Hz, 1H), 5.56 (dt, *J* = 6.4, 16 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 13.6, 14.6, 22.4, 23.0, 23.6, 25.6, 27.4, 28.2, 29.3, 30.1, 32.4, 40.6, 42.0, 42.4, 48.0, 50.8, 66.7, 70.2, 71.3, 103.7, 124.8, 138.6, 176.3;IR (neat, cm^{-1}) 3299, 2956, 2869, 2760, 1719, 1637, 1457, 1364, 1268, 1243, 1128, 1070, 730; HRMS (EI) *m/z* calcd. for $C_{27}H_{51}N_3O_3$ 465.39 [M^+]; found: 465.3937.



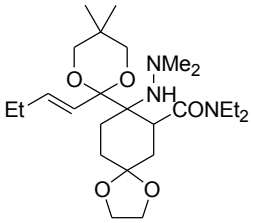
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-5-phenylcyclohexanecarboxamide (**2'n**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.64 (s, 3H), 1.05 (m, 6H), 1.16-1.23 (m, 6H), 1.47 (m, 1H), 1.73 (m, 2H), 1.95 (m, 1H), 2.11 (m, 2H), 2.41 (m, 1H), 2.57-2.63 (m, 7H), 2.96 (m, 1H), 3.11-3.21 (m, 2H), 3.31 (m, 2H), 3.42-3.60 (m, 3H), 3.69 (m, 2H), 4.38 (br, 1H), 5.08 (d, *J* = 16.5 Hz, 1H), 5.66 (dt, *J* = 6.4, 16 Hz, 1H), 7.15-7.30 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 13.5, 14.6, 22.4, 23.6, 25.5, 28.3, 30.1, 30.6, 34.9, 40.6, 41.9, 42.5, 44.3, 47.9, 50.9, 66.7, 70.1, 71.3, 103.6, 124.6, 125.8, 126.9, 128.2, 138.7, 147.3, 175.5; IR (neat, cm^{-1}) 3300, 2954, 2869, 2761, 1703, 1684, 1636, 1448, 1361, 1264, 1129, 1095, 1071, 909, 732, 699; HRMS (EI) *m/z* calcd. for $C_{29}H_{47}N_3O_3$ 485.36 [M^+]; found: 485.3616.



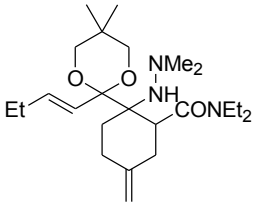
(*E*)-5-(benzyloxy)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclohexanecarboxamide (**2'o**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.56 (s, 3H), 0.99 (m, 6H), 1.07 (s, 3H), 1.12 (t, *J* = 6.9 Hz, 3H), 1.52 (m, 1H), 1.77 (m, 2H), 1.85 (m, 1H), 2.04 (m, 2H), 2.16 (m, 2H), 2.39-2.46 (m, 7H), 2.95 (m, 1H), 3.10-3.27 (m, 3H), 3.38-3.64 (m, 5H), 4.14 (br, 1H), 4.49 (m, 2H), 5.02 (d, *J* = 16.5 Hz, 1H), 5.56 (dt, *J* = 6.4, 16.5 Hz, 1H), 7.19-7.29 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 13.5, 14.3, 22.5, 23.7, 25.5, 25.6, 30.1, 32.5, 36.0, 40.5, 42.5, 50.8, 67.0, 69.2, 70.2, 71.1, 72.9, 103.7, 124.9, 126.9, 128.1, 138.4, 139.8, 176.1; IR (neat, cm^{-1}) 2927, 2857, 1748, 1634, 1557, 1540, 1507, 1455, 1362, 1075, 733, 669; HRMS (EI) *m/z* calcd. for $C_{30}H_{49}N_3O_3$ 515.37 [M^+]; found: 515.3733.



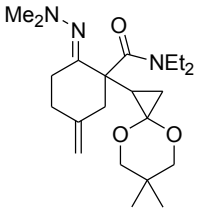
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-5,5-dimethylcyclohexanecarboxamide (**2'p**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 3H), 0.92 (s, 3H), 0.95 (s, 3H), 1.05 (m, 6H), 1.14-1.21 (m, 7H), 1.63-1.83 (m, 2H), 1.99-2.13 (m, 3H), 2.25 (m, 1H),2.51 (s, 6H), 3.00 (m, 1H), 3.14 (m, 2H), 3.28 (m, 2H), 3.51 (m, 2H), 3.65 (m, 2H), 4.25 (br, 1H), 5.05 (d, *J* = 16 Hz, 1H), 5.63 (dt, *J* = 6.4, 16.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 13.5, 14.3, 22.5, 23.6, 23.8, 24.6, 25.5, 30.1, 30.3, 32.7, 34.9, 37.2, 40.5, 40.8, 42.3, 50.8, 67.1, 70.1, 71.2, 103.7, 124.8, 138.5, 176.1; IR (neat, cm^{-1}) 3299, 2951, 2803, 2761, 2238, 1636, 1450, 1395, 1362, 1285, 1251, 1219, 1122, 1069, 975, 911, 794, 731; HRMS (EI) *m/z* calcd. for $C_{25}H_{47}N_3O_3$ 437.36 [M^+]; found: 437.3623.



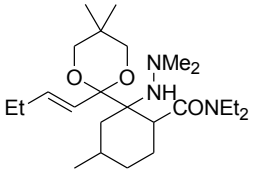
(*E*)-8-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-8-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-1,4-dioxaspiro[4.5]decane-7-carboxamide (**2'q**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 3H), 1.05 (m, 6H), 1.13 (s, 3H), 1.21 (t, *J* = 7.3 Hz, 3H), 1.33 (d, *J* = 12.8 Hz, 1H), 1.61 (m, 1H), 1.85 (m, 1H), 1.97-2.13 (m, 3H), 2.42-2.52 (m, 8H), 3.02 (m, 1H), 3.18 (m, 1H), 3.26-3.34 (m, 3H), 3.50 (m, 1H), 3.59-3.70 (m, 3H), 3.95 (m, 4H), 4.22 (br, 1H), 5.05 (d, *J* = 16.5 Hz, 1H), 5.65 (dt, *J* = 6.4, 16.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 13.5, 14.3, 22.5, 23.7, 25.5, 26.0, 30.1, 31.1, 36.2, 39.5, 40.7, 42.5, 50.9, 64.3, 66.5, 70.2, 71.1, 103.4, 109.2, 124.6, 138.8, 174.8; IR (neat, cm^{-1}) 2936, 2871, 2761, 1636, 1450, 1362, 1270, 1104, 1039, 1006, 944, 842; HRMS (EI) *m/z* calcd. for $C_{25}H_{45}N_3O_3$ 467.34 [M^+]; found: 467.3362.



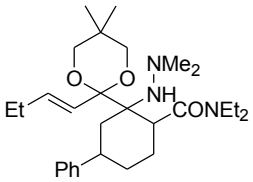
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-5-methylenecyclohexanecarboxamide (**2'r**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.62 (s, 3H), 1.00-1.12 (m, 9H), 1.18 (t, *J* = 7.3 Hz, 3H), 1.70 (m, 1H), 1.88 (d, *J* = 12.4 Hz, 1H), 2.10 (m, 3H),2.47-2.58 (m, 7H), 2.89 (t, *J* = 12.8 Hz, 1H), 2.98-3.14 (m, 3H), 3.27 (d, *J* = 10.5 Hz, 2H), 3.44-3.69 (m, 5H), 4.22 (br, 1H), 4,55 (s, 1H), 4.60 (s, 1H), 5.00 (d, *J* = 16 Hz, 1H), 5.66 (dt, *J* = 6.4, 16.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.2, 14.8, 15.9, 23.6, 24.8, 26.8, 30.5, 31.3, 32.2, 38.8, 42.0, 43.7, 44.4, 52.2, 68.2, 71.4, 72.5, 104.7, 106.7, 125.8, 140.2, 151.0, 176.3; IR (neat, cm^{-1}) 3292, 2934, 2870, 2803, 2761, 1635, 1450, 1395, 1362, 1278, 1259, 1219, 1126, 1106, 1010, 945, 881, 797; HRMS (EI) *m/z* calcd. for $C_{24}H_{43}N_3O_3$ 421.33 [M^+]; found: 421.3305.



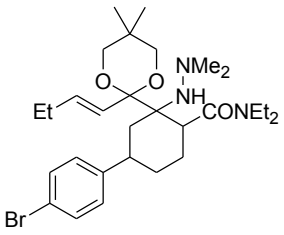
(*E*)-1-(6,6-dimethyl-4,8-dioxaspiro[2.5]octan-1-yl)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5-methylenecyclohexanecarboxamide (**3r**) ; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.78 (s, 3H), 0.84 (m, 1H), 0.94-1.06 (m, 7H), 1.15 (s, 3H), 1.25 (m, 1H), 1.99 (m, 2H), 2.18 (m, 1H), 2.47-2.52 (m, 6H), 2.70 (m, 1H), 2.92 (m, H), 3.07-3.15 (m, 2H), 3.24 (m, 1H), 3.38-3.56 (m, 4H), 3.64 (m, 1H), 3.80 (m, 1H), 4.82 (s, 1H), 4.92 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.5, 13.3, 14.5, 21.8, 22.9, 27.0, 28.5, 30.5, 34.7, 40.0, 40.8, 45.1, 47.8, 52.6, 75.3, 76.1, 90.6, 111.3, 143.9, 170.1, 170.2; IR (neat, cm^{-1}) 3473, 3075, 2953, 2855, 2816, 2772, 2237, 1626, 1421, 1377, 1362, 1297, 1265, 1237, 1217, 1165, 1099, 1069, 1047, 970, 919, 891, 826, 791, 730; HRMS (EI) *m/z* calcd. for $C_{22}H_{37}N_3O_3$ 391.28 [M^+]; found: 391.2842.



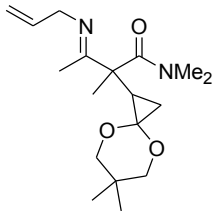
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-4-methylcyclohexanecarboxamide (**2's**) ; white solid of mp = 107 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.56 (s, 3H), 0.83 (d, *J* = 6.4 Hz, 3H), 0.98 (m, 6H), 1.07-1.15 (m, 8H), 1.27 (m, 1H), 1.60 (m, 1H), 2.02 (m, 3H), 2.34 (m, 1H), 2.42 (s, 6H), 2.75 (d, *J* = 12.4 Hz, 1H), 2.91 (m, 1H), 3.09 (m, 1H), 3.22 (d, 11 Hz, 2H), 3.46 (m, 2H), 3.60 (m, 2H), 4.27 (br, 1H), 5.00 (d, *J* = 16 Hz, 1H), 5.56 (dt, *J* = 6.4, 16 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 14.6, 22.5, 22.8, 23.7, 25.6, 27.6, 28.6, 30.1, 34.8, 36.6, 40.6, 41.6, 42.5, 50.9, 67.7, 70.2, 71.2, 103.8, 124.8, 138.4, 176.3; IR (neat, cm^{-1}) 3422, 2952, 2866, 2816, 2772, 2233, 1638, 1457, 1378, 1361, 1311, 1261, 1220, 1146, 1099, 1021, 972, 862, 817, 783, 731; HRMS (EI) *m/z* calcd. for $C_{24}H_{45}N_3O_3$ 423.35 [M^+]; found: 423.3468.



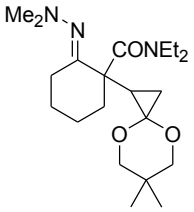
(*E*)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-4-phenylcyclohexanecarboxamide (**2't**) ; white solid of mp = 112 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.55 (s, 3H), 0.95 (t, *J* = 7.3 Hz, 3H), 1.02 (m, 6H), 1.15 (t, *J* = 7.3 Hz, 3H), 1.41 (m, 2H), 1.60 (m, 1H), 1.81 (m, 1H), 2.02 (m, 2H), 2.21 (m, 1H), 2.48 (s, 6H), 2.56 (m, 1H), 2.95 (m, 2H), 3.07-3.25 (m, 4H), 3.42-3.64 (m, 4H), 4.40 (br, 1H), 5.02 (d, *J* = 16 Hz, 1H), 5.58 (dt, *J* = 6.4, 16 Hz, 1H), 7.08-7.28 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 14.6, 22.5, 23.7, 25.5, 28.9, 30.0, 33.6, 35.6, 38.9, 40.6, 41.4, 42.5, 50.9, 67.9, 70.2, 71.2, 103.7, 124.7, 125.4, 127.0, 128.0, 138.6, 148.1, 176.1; IR (neat, cm^{-1}) 3300, 2934, 2870, 2803, 2761, 1632, 1451, 1395, 1378, 1278, 1249, 1218, 1125, 1063, 1010, 946, 754, 699, 664; HRMS (EI) *m/z* calcd. for $C_{29}H_{47}N_3O_3$ 485.36 [M^+]; found: 485.3626.



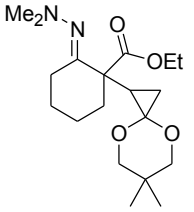
(*E*)-4-(4-bromophenyl)-2-(2-(but-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclohexanecarboxamide (**2'u**) ; white solid of mp = 83 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.62 (s, 3H), 1.02 (t, *J* = 7.3 Hz, 3H), 1.09 (m, 6H), 1.21 (t, *J* = 7.3 Hz, 3H), 1.45 (m, 2H), 1.64 (m, 1H), 1.87 (m, 1H), 2.09 (m, 2H), 2.24 (m, 1H), 2.55 (s, 6H), 2.62 (m, 1H), 2.96-3.31 (m, 6H), 3.48-3.70 (m, 4H), 4.43 (br, 1H), 5.06 (d, *J* = 16 Hz, 1H), 5.65 (dt, *J* = 6.4, 16 Hz, 1H), 7.15 (d, *J* = 8.2 Hz, 2H), 7.38 (d, *J* = 8.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 13.5, 14.6, 22.4, 23.7, 25.5, 28.7, 30.0, 33.3, 35.5, 38.5, 40.6, 41.3, 42.5, 50.9, 67.8, 70.2, 71.2, 103.6, 119.0, 124.5, 128.8, 131.0, 138.8, 147.1, 175.9; IR (neat, cm^{-1}) 3295, 2934, 2870, 2804, 2761, 1633, 1487, 1451, 1362, 1248, 1218, 1125, 1071, 1009, 946, 817, 752, 665; HRMS (EI) *m/z* calcd. for $C_{29}H_{46}BrN_3O_3$ 563.27 [M^+]; found: 563.2732.



(*E*)-3-(allylimino)-2-(6,6-dimethyl-4,8-dioxaspiro[2.5]octan-1-yl)-*N,*N,2-trimethylbutanamide (**3c**); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.76 (m, 1H), 0.83 (s, 3H), 1.01 (m, 1H), 1.10 (s, 3H), 1.21 (s, 3H), 1.83 (s, 3H), 2.47 (m, 1H), 2.95 (m, 6H), 3.54 (m, 4H), 4.00 (m, 2H), 5.09 (d, *J* = 10.5 Hz, 1H), 5.21 (d, *J* = 17.4 Hz, 1H), 5.99 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 16.6, 23.2, 23.6, 24.3, 30.6, 32.2, 38.7, 39.0, 55.4, 77.0, 78.0, 78.8, 91.5, 116.8, 137.3, 173.0, 175.2; IR (neat, cm^{-1}) 3484, 2954, 2868, 1634, 1539, 1472, 1385, 1299, 1172, 1077, 1047, 917, 687; HRMS (EI) *m/z* calcd. for $C_{18}H_{30}N_2O_3$ 322.23 [M^+]; found: 322.2251.



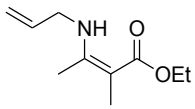
(*E*)-1-(6,6-dimethyl-4,8-dioxaspiro[2.5]octan-1-yl)-2-(2,2-dimethylhydrazono)-N,N-die thylcyclohexanecarboxamide (**3f**); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.75-0.78 (m, 4H), 0.93 (m, 1H), 0.98 (t, *J* = 6.9 Hz, 3H), 1.08 (t, *J* = 7.3 Hz, 3H), 1.14 (s, 3H), 1.18-1.21 (m, 1H), 1.33-1.42 (m, 1H), 1.57-1.61 (m, 1H), 1.76-2.00 (m, 3H), 2.45-2.50 (m, 7H), 2.65 (dd, *J* = 8.7, 11.4 Hz, 1H), 2.97-3.13 (m, 2H), 3.23-3.27 (m, 1H), 3.40-3.67 (m, 5H), 3.80-3.89 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.7, 13.2, 14.1, 21.9, 22.9, 27.6, 27.8, 28.9, 30.5, 39.0, 40.5, 41.1, 47.7, 52.3, 75.3, 76.1, 90.9, 170.2, 171.0; IR (neat, cm^{-1}) 2953, 2857, 2815, 2771, 1734, 1644, 1623, 1449, 1362, 1302, 1271, 1218, 1166, 1100, 1078, 1046, 1019, 983, 840, 790; HRMS (EI) *m/z* calcd. $C_{21}H_{37}N_3O_3$ 379.2835 [M^+]; found: 379.2832.



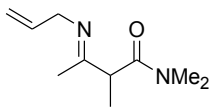
(*E*)-ethyl 1-(6,6-dimethyl-4,8-dioxaspiro[2.5]octan-1-yl)-2-(2,2-dimethylhydrazono) cyclohexane carboxylate (**3g**); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.81 (s, 3H), 0.89 (m, 1H), 0.92 (m, 1H), 1.06 (s, 3H), 1.17 (t, *J* = 7.3 Hz, 3H), 1.41 (m, 2H), 1.61 (m, 2H), 1.75 (m, 2H), 2.11 (m, 1H), 2.45 (s, 6H), 3.28-3.40 (m, 3H), 3.50 (d, *J* = 10.0 Hz, 1H), 3.98-4.09 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.9, 15.3, 23.3, 24.3, 24.4, 27.6, 28.5, 32.0, 33.0, 40.0, 48.8, 54.1, 62.3, 75.9, 77.0, 90.8, 170.2, 173.2;IR (neat, cm^{-1}) 3445, 2952, 2861, 2817, 2773, 1731, 1634, 1539, 1471, 1448, 1363, 1307, 1283, 1245, 1219, 1173, 1137, 1078, 1021, 985, 968, 920, 858, 799; HRMS (EI) *m/z* calcd. for $C_{19}H_{32}N_2O_4$ 352.24 [M^+]; found: 352.2358.

Substrate Synthesis

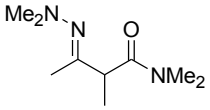
General Procedure for the Synthesis of 1f: To the solution of ethyl-2-oxocyclohexanecarboxylate (850 mg, 5 mmol) in toluene (0.5 mL), diethylamine (5 equiv) was added and heated to reflux. After stirred 15 h, the whole was cooled at room temperature and the solvent was evaporated. The crude product was purified by silica gel column chromatography (hexane/AcOEt = 6/1 to 1/1). To the solution of ketoamide in 1,1-dimethylhydrazine (5 mL) was added trimethylsilyl chloride (2.0 equiv). The mixture was stirred for overnight at room temperature. The reaction mixture was quenched with sat. NH_4Cl aq. The organic layer was extracted with $CHCl_3$. The combined organic extracts were dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane/AcOEt = 1/1) to give the product **1f** in 68% yield.



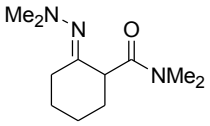
(*Z*)-ethyl 3-(allylamino)-2-methylbut-2-enoate (**1b**); yellow oil was obtained in 94%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.20 (t, *J* = 5.5 Hz, 3H), 1.71 (s, 3H), 1.86 (s, 3H), 3.75 (m, 2H), 4.05 (q, *J* = 5.5 Hz, 2H), 5.06 (d, *J* = 10.5 Hz, 1H), 5.13 (d, *J* = 16.9 Hz, 1H), 5.75-5.84 (m, 1H), 9.27 (br, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.6, 14.6, 14.9, 45.4, 58.6, 87.1, 115.5, 135.3, 159.4, 171.0; IR (neat, cm^{-1}) 3255, 3168, 3084, 2979, 2930, 1716, 1644, 1597, 1445, 1388, 1364, 1236, 1175, 1097, 1031, 992, 919, 858, 779; HRMS (EI) *m/z* calcd. for $C_{10}H_{17}NO_2$ 183.1259 [M^+]; found: 183.1254.



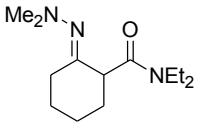
(*E*)-3-(allylimino)-*N,N*,2-trimethylbutanamide (**1c**); yellow oil was obtained in 97%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.74 (s, 3H), 1.17 (d, *J* = 6.8 Hz, 3H), 1.68 (s, 3H), 2.81 (s, 3H), 2.93 (s, 3H), 3.54 (m, 1H), 3.82 (m, 2H), 4.96 (d, *J* = 10.1 Hz, 1H), 5.03 (d, *J* = 17.4 Hz, 1H), 5.85 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 13.6, 14.7, 26.8, 35.3, 36.8, 37.1, 49.5, 51.1, 53.3, 114.8, 115.2, 135.1, 169.5, 171.3; IR (neat, cm^{-1}) 3288, 3078, 2934, 1723, 1642, 1495, 1396, 1321, 1258, 1152, 1080, 996, 916, 836, 792, 752, 701; HRMS (EI) *m/z* calcd. for $C_{10}H_{18}N_2O$ 182.14 [M^+]; found: 182.1422.



(*E*)-3-(2,2-dimethylhydrazono)-*N,N*,2-trimethylbutanamide (**1d**) ; colorless oil was obtained in 96%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.29 (d, *J* = 6.8 Hz, 3H), 1.91 (s, 3H), 2.47 (s, 3H), 2.94 (s, 3H), 3.04 (s, 3H), 3.63 (q, *J* = 6.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 14.5, 15.0, 18.5, 35.4, 36.1, 36.8, 38.1, 45.9, 46.4, 47.1, 166.1, 167.7, 170.8, 171.0; IR (neat, cm^{-1}) 3498, 2952, 2857, 2817, 2774, 1650, 1467, 1395, 1315, 1270, 1197, 1152, 1081, 1022, 982, 958, 845, 785, 732; HRMS (EI) *m/z* calcd. for $C_9H_{19}N_3O$ 185.15 [M^+]; found: 185.1531.

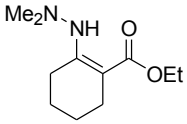


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-dimethylcyclohexanecarboxamide (**1e**); yellow oil was obtained in 52%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.52-2.06 (m, 6H), 2.44 (s, 6H), 2.51-2.61 (m, 1H), 2.75-2.82 (m, 1H), 2.93 (s, 3H), 2.99 (s, 3H), 3.45 (t, *J* = 5.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) 21.6, 23.0, 26.0, 27.2, 27.6, 29.3, 29.7, 33.7, 35.3, 35.6, 36.9, 37.2, 39.7, 47.2, 47.3, 47.4, 167.4, 169.8, 171.1, 171.9; IR (neat, cm^{-1}) 3473, 2937, 2857, 2816, 2773, 1711, 1644, 1496, 1448, 1396, 1351, 1259, 1152, 1078, 1021, 998, 971, 930, 851, 713; HRMS (EI) *m/z* calcd. for $C_{11}H_{21}N_3O$ 211.1685 [M^+]; found: 211.1689.

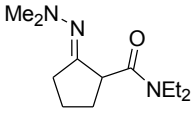


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethylcyclohexanecarboxamide (**1f**) ; yellow oil was obtained in 68%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.08-1.21 (m, 6H), 1.44-1.71 (m, 3H), 1.78-1.85 (m, 1H), 1.94-2.08 (m, 2H), 2.38-2.42 (m, 6H), 2.48 (m, 1H), 2.76 (m, 1H), 3.13-3.57 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.3, 12.5, 13.9, 14.3, 21.4, 23.0, 26.0, 26.9, 27.5, 29.7, 29.9, 33.7, 39.3, 39.5, 39.9, 41.2, 47.0, 47.2, 167.2, 170.3, 170.8; IR (neat, cm^{-1}) 3481, 2935, 2857, 2816, 2772, 2237, 1713, 1638, 1447, 1379, 1361,

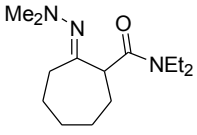
1318, 1258, 1219, 1138, 1098, 1079, 1021, 992, 967, 924, 891, 845, 793, 731; HRMS (EI) *m/z* calcd. for $C_{13}H_{25}N_3O$ 239.20 [M^+]; found: 239.2000.



ethyl 2-(2,2-dimethylhydrazinyl)cyclohex-1-enecarboxylate (**1g**); yellow oil was obtained in 83%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.25 (m, 3H), 1.55 (m, 4H), 1.73 (m, 1H), 2.25 (m, 2H), 2.49 (m, 7H), 4.12 (m, 2H), 9.22 (br, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.4, 21.9, 22.5, 23.4, 25.6, 47.0, 48.5, 58.5, 88.8, 159.4, 170.3; IR (neat, cm^{-1}) 3220, 3165, 2938, 2856, 2774, 1731, 1651, 1596, 1447, 1362, 1339, 1246, 1178, 1156, 1081, 1062, 1034, 975, 913, 874, 826, 775; HRMS (EI) *m/z* calcd. for $C_{11}H_{20}N_2O_2$ 212.15 [M^+]; found: 212.1522.

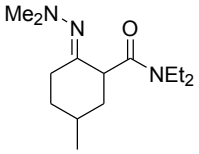


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethylcyclopentanecarboxamide (**1h**); yellow oil was obtained in 54%; ^{1}H NMR (400 MHz, $CDCl_3$) d 1.08-1.21 (m, 6H), 1.24 (t, *J* = 7.3 Hz, 3H), 1.71 (m, 1H), 1.90-2.18 (m, 3H), 2.34-2.63 (m, 7H), 3.27 (m, 2H), 3.54 (m, 2H), 3.71 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) d 12.4, 12.6, 14.3, 23.1, 23.2, 28.4, 29.4, 33.5, 39.7, 40.3, 41.8, 42.5, 43.6, 46.6, 46.7, 171.5, 171.6, 171.9, 178.8; IR (neat, cm^{-1}) 3483, 2966, 2855, 2816, 2772, 1636, 1431, 1378, 1361, 1326, 1307, 1250, 1220, 1142, 1116, 1098, 1021, 970, 822, 789, 736; HRMS (EI) *m/z* calcd. for $C_{12}H_{23}N_3O$ 225.18 [M^+]; found: 225.1845.

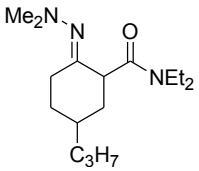


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethylcycloheptanecarboxamide (**1i**); yellow oil was obtained in 34%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.06-1.27 (m, 7H), 1.30-1.47 (m, 2H), 1.78-2.03 (m, 5H), 2.32-2.41 (m, 6H), 2.55-2.69 (m, 1H), 3.00-3.68 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.4, 12.5, 13.8, 14.4, 26.5, 26.6, 27.6, 28.5, 28.6, 29.0, 29.5,

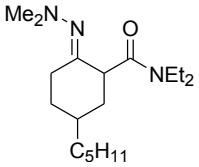
29.9, 30.0, 35.4, 39.7, 39.9, 41.5, 41.9, 44.4, 46.5, 47.1, 49.5, 171.5, 171.8, 173.1, 175.5; IR (neat, cm^{-1}) 3469, 2929, 2853, 2814, 2770, 2237, 1706, 1637, 1446, 1378, 1362, 1317, 1253, 1219, 1150, 1124, 1098, 1021, 957, 924, 731; HRMS (EI) *m/z* calcd. for $C_{14}H_{27}N_3O$ 253.2154 [M^+]; found: 253.2148.



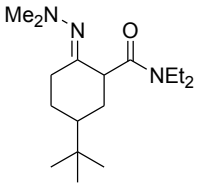
(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5-methylcyclohexanecarboxamide (**1j**) ; yellow oil was obtained in 24%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.77-1.12 (m, 10H), 1.61-1.77 (m, 4H), 2.13-2.36 (m, 7H), 2.87-3.67 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.31, 12.0, 12.7, 14.4, 21.5, 26.4, 27.2, 27.4, 27.9, 31.3, 33.7, 34.1, 34.3, 35.3, 38.0, 39.3, 39.8, 40.1, 41.1, 41.5, 41.8, 47.3, 46.2, 47.2, 47.4, 47.5, 165.7, 168.6, 170.6, 171.4; IR (neat, cm^{-1}) 3458, 2951, 2855, 2816, 2772, 1715, 1639, 1456, 1378, 1361, 1277, 1254, 1219, 1137, 1096, 1020, 970, 909, 876, 795, 687; HRMS (EI) *m/z* calcd. for $C_{14}H_{27}N_3O$ 253.22 [M^+]; found: 253.2144.



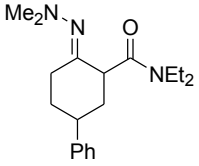
(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5-propylcyclohexanecarboxamide (**1k**) ; yellow oil was obtained in 33%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.74 (t, *J* = 7.3 Hz, 3H), 0.99 (m, 7H), 1.09-1.22 (m, 4H), 1.41-1.88 (m, 5H), 2.16-2.47 (m, 6H), 2.84-3.43 (m, 5H), 3.58 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.9, 12.5, 13.8, 13.9, 14.2, 26.1, 27.6, 29.8, 31.5, 31.7, 31.9, 32.1, 33.0, 33.4, 33.8, 34.6, 35.2, 35.9, 38.2, 38.4, 39.0, 39.5, 39.8, 40.9, 41.3, 41.5, 45.9, 46.9, 47.0, 47.2, 47.3, 50.6, 165.8, 168.5, 170.5, 171.1; IR (neat, cm^{-1}) 3446, 2955, 2856, 2816, 2772, 1715, 1642, 1460, 1378, 1361, 1277, 1220, 1145, 1098, 1021, 970, 795, 731, 685; HRMS (EI) *m/z* calcd. for $C_{16}H_{31}N_3O$ 281.25 [M^+]; found: 281.2474.



(*Z*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5-pentylcyclohexanecarboxamide (**1l**) ; yellow oil was obtained in 56%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.73 (m, 3H), 0.93-1.06 (m, 8H), 1.13 (m, 8H), 1.42-1.66 (m, 2H), 1.80 (m, 2H), 2.16-2.31 (m, 6H),2.87-3.44 (m, 5H), 3.60 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.0, 12.6, 13.8, 14.3, 22.4, 26.3, 26.4, 26.5, 27.8, 30.1, 31.8, 31.9, 32.1, 32.3, 33.3, 33.6, 34.3, 34.8, 36.0, 36.1, 39.1, 39.6, 40.0, 41.0, 41.7, 43.7, 46.2, 47.1, 47.2, 47.3, 47.4, 47.5, 165.9, 168.7, 170.6, 171.3; IR (neat, cm^{-1}) 3470, 2927, 2854, 2815, 2771, 2232, 1715, 1643, 1460, 1378, 1360, 1345, 1275, 1220, 1144, 1114, 1098, 1021, 970, 886, 795, 730, 686; HRMS (EI) *m/z* calcd. for $C_{18}H_{35}N_3O$ 309.28 [M^+]; found: 309.2771.

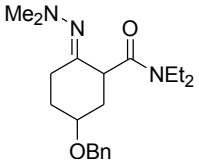


(*E*)-5-(tert-butyl)-2-(2,2-dimethylhydrazono)-*N,N*-diethylcyclohexanecarboxamide (**1m**) ; yellow oil was obtained in 26%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.86-0.94 (m, 9H), 1.06-1.46 (m, 8H), 1.68-1.85 (m, 2H), 1.91-2.04 (m, 2H), 2.38-2.46 (m, 6H), 3.01-3.78 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.0, 12.7, 14.0, 14.4, 26.8, 27.1, 27.4, 28.0, 30.7, 31.1, 32.0, 32.4, 34.0, 39.2, 39.5, 39.8, 41.0, 41.6, 46.5, 47.2, 47.4, 47.8, 50.6, 165.8, 168.6, 170.8, 171.5; IR (neat, cm^{-1}) 2961, 2868, 2816, 2773, 1716, 1638, 1461, 1365, 1277, 1220, 1132, 1096, 1022, 985, 798; HRMS (EI) *m/z* calcd. for $C_{17}H_{33}N_3O$ 295.26 [M^+]; found: 295.2623.

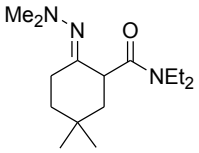


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5-phenylcyclohexanecarboxamide (**1n**) ; yellow oil was obtained in 15%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.08 (m, 6H), 1.18 (m, 1H), 1.61 (m, 1H), 1.88 (m, 1H), 2.04 (m, 1H), 2.26 (m, 2H), 2.36-2.42 (m, 6H), 2.80 (m, 1H),2.99 (m, 1H), 3.15-3.36 (m, 3H), 3.67 (m, 1H), 7.08-7.21 (m, 5H); ^{13}C NMR

(100 MHz, $CDCl_3$) δ 12.1, 12.8, 12.9, 14.2, 14.6, 15.2, 26.8, 28.3, 33.1, 33.9, 34.1, 34.2, 34.3, 36.6, 36.8, 37.2, 37.4, 38/5, 38.7, 39.4, 39.5, 40.0, 40.2, 40.4, 41.3, 41.7, 41.8, 41.9, 42.0, 42.3, 42.9, 46.4, 47.4, 47.6, 47.9, 53.8, 65.8, 126.1, 126.3, 126.7, 126.8, 128.4, 128.5, 165.0, 167.8, 168.1, 169.6, 170.3, 170.5, 171.3; IR (neat, cm^{-1}) 3421, 2932, 2857, 2816, 2772, 1716, 1637, 1456, 1430, 1362, 1270, 1219, 1134, 1097, 1022, 981, 758, 700; HRMS (EI) *m/z* calcd. for $C_{19}H_{29}N_3O$ 315.23 [M^+]; found: 315.2309.

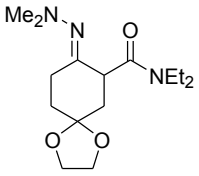


(*E*)-5-(benzyloxy)-2-(2,2-dimethylhydrazono)-*N,N*-diethylcyclohexanecarboxamide (**1o**) ; yellow oil was obtained in 12%; ^1H NMR (400 MHz, $CDCl_3$) δ 1.02 (m, 6H), 1.14 (m, 1H), 1.65-1.88 (m, 2H), 2.13-2.36 (m, 7H), 2.59 (m, 1H), 2.98-3.61 (m, 5H), 4.00 (m, 1H), 4.46 (m, 2H), 7.13- 7.23 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 3.2, 14.0, 14.3, 14.6, 16.0, 16.1, 16.4, 22.9, 25.6, 27.3, 31.5, 32.3, 33.1, 33.4, 34.0, 34.1, 36.2, 36.5, 36.8, 40.9, 41.3, 41.6, 42.2, 43.1, 43.5, 46.0, 47.4, 49.3, 49.4, 62.2, 71.8, 72.3, 72.6, 74.7, 75.4, 77.0,129.3, 129.4, 130.2, 140.5, 140.6, 166.3, 168.1, 170.8, 171.6, 172.4, 172.7, 173.0; IR (neat, cm^{-1}) 3462, 3062, 3029, 2933, 2857, 2817, 2773, 1717, 1643, 1454, 1362, 1306, 1251, 1219, 1096, 1027, 970, 910, 889, 838, 792, 735, 698; HRMS (EI) *m/z* calcd. for $C_{20}H_{31}N_3O$ 345.24 [M^+]; found: 345.2414.

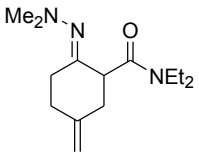


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5,5-dimethylcyclohexanecarboxamide (**1p**) ; yellow solid of mp = 68 °C was obtained in 48%; ^1H NMR (400 MHz, $CDCl_3$) δ 1.01 (s, 3H), 1.06 (s, 3H), 1.14 (m, 6H), 1.40-1.62 (m, 3H), 1.95-2.07 (m, 2H), 2,32-2.42 (m, 6H), 3.04-3.41 (m, 5H), 3.68 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.7, 12.1, 13.6, 14.1, 24.0, 24.4, 28.2, 29.6, 29.7, 30.3, 31.0, 37.1, 37.8, 38.9, 39.0, 39.6, 40.7, 40.8, 41.7, 43.2, 46.6, 46.9, 165.4, 170.4, 171.0, 171.4; IR (neat, cm^{-1}) 2948, 2854, 2816, 2769, 1638, 1464, 1379, 1364, 1344, 1306, 1280, 1235, 1220, 1177, 1154, 1118, 1099, 1081, 1024, 972, 943, 885, 793, 718, 693; HRMS (EI) *m/z* calcd. for

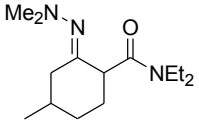
$C_{15}H_{29}N_3O$ 267.23 [M^+]; found: 267.2306.



(*E*)-8-(2,2-dimethylhydrazono)-*N,N*-diethyl-1,4-dioxaspiro[4.5]decane-7-carboxamide (**1q**) ; yellow oil was obtained in 23%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.01-1.19 (m, 6H), 1.61-2.11 (m, 5H), 2.21-2.43 (m, 7H), 2.86-3.70 (m, 5H), 3.82-3.94 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.9, 14.3, 24.8, 33.5, 37.3, 39.3, 41.2, 44.8, 47.3, 64.3, 108.0, 163.8, 169.7; IR (neat, cm^{-1}) 2975, 2948, 2875, 2823, 2784, 1643, 1461, 1431, 1379, 1359, 1304, 1270, 1245, 1220, 1144, 1118, 1059, 1031, 967, 951, 909, 882, 789, 716, 695; HRMS (EI) *m/z* calcd. for $C_{15}H_{27}N_3O$ 297.21 [M^+]; found: 297.2045.

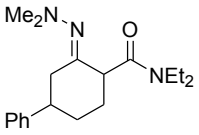


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-5-methylenecyclohexanecarboxamide (**1r**) ; yellow oil was obtained in 16%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.06 (t, *J* = 7.4 Hz, 3H), 1.16 (t, *J* = 7.4 Hz, 3H), 1.25-1.40 (m, 4H), 2.03-2.21 (m, 2H), 2.39 (s, 6H), 2.75 (m, 1H), 3.16 (m, 2H), 3.18 (m, 2H), 3.46 (m, 2H), 3.74 (m, 1H), 4.77 (d, *J* = 8.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.3, 12.7, 14.1, 14.4, 27.9, 33.1, 33.2, 33.6, 37.0, 37.3, 39.5, 39.9, 41.0, 41.3, 41.5, 47.3, 47.4, 48.0, 110.0, 110.6, 143.4, 144.8, 165.7, 469.8, 170.1, 170.1; IR (neat, cm^{-1}) 3421, 2933, 2853, 1717, 1639, 1431, 1379, 1270, 1219, 1132, 1071, 889, 796; HRMS (EI) *m/z* calcd. for $C_{14}H_{25}N_3O$ 251.20 [M^+]; found: 251.2002.

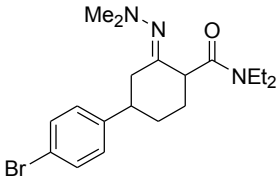


(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-4-methylcyclohexanecarboxamide (**1s**) ; yellow oil was obtained in 14%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.80-0.88 (m, 3H), 0.94-1.12 (m, 7H), 1.34-1.94 (m, 5H), 2.21-2.31 (m, 6H), 2.86-3.42 (m, 5H), 3.61 (m,

1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.3, 12.0, 12.2, 12.4, 12.6, 12.7, 19.1, 20.7, 22.0, 22.1, 23.6, 25.9, 27.4, 28.9, 29.0, 29.3, 30.0, 30.4, 32.1, 32.8, 33.1, 34.4, 34.5, 34.8, 36.3, 38.6, 39.2, 39.7, 39.9, 40.0, 40.3, 41.0, 41.2, 41.3, 41.7, 42.0, 45.5, 47.2, 47.4, 47.5, 165.7, 165.9, 168.6, 169.2, 170.4, 170.7, 171.2; IR (neat, cm^{-1}) 2953, 2816, 2772, 2234, 1640, 1458, 1378, 1311, 1261, 1220, 1126, 1098, 1021, 972, 923, 842, 803, 731; HRMS (EI) *m/z* calcd. for $C_{14}H_{27}N_3O$ 253.22 [M^+]; found: 253.2152.

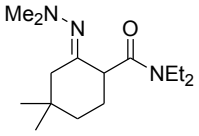


(*Z*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-4-phenylcyclohexanecarboxamide (**1t**) ; yellow solid of mp = 102 °C was obtained in 9%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.94-1.08 (m, 6H), 1.55-2.03 (m, 4H), 2.22-2.31 (m, 6H), 2.42-3.66 (m, 8H),7.03-7.19 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.1, 12.0, 12.6, 12.7, 14.0, 14.3, 14.4, 28.9, 29.0, 29.2, 29.3, 32.2, 33.4, 33.9, 35.1, 35.4, 38.4, 39.2, 39.8, 40.1, 41.0, 41.1, 41.4, 41.8, 42.8, 43.0, 43.3, 43.9, 45.1, 47.1, 47.3, 126.0, 126.2, 126.4, 126.6, 126.7, 128.1, 128.2, 144.8, 145.2, 145.5, 164.8, 167.7, 169.8, 170.1, 170.4, 171.1; IR (neat, cm^{-1}) 3027, 2933, 2855, 2817, 2772, 1635, 1449, 1378, 1309, 1265, 1218, 1142, 1100, 1025, 959, 943, 874, 784, 759, 719, 698; HRMS (EI) *m/z* calcd. for $C_{19}H_{29}N_3O$ 315.23 [M^+]; found: 315.2317.



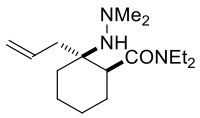
(*E*)-4-(4-bromophenyl)-2-(2,2-dimethylhydrazono)-*N,N*-diethylcyclohexanecarboxamid e (**1u**) ; yellow solid of mp = 99 °C was obtained in 11%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.94-1.11 (m, 6H), 1.52-1.70 (m, 2H), 1.85-2.03 (m, 2H), 2.22-2.30 (m, 6H), 2.37-3.62 (m, 8H),6.92-7.05 (m, 2H), 7.20-7.29 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.1, 12.0, 12.6, 12.7, 14.0, 14.3, 14.4, 24.2, 28.6, 28.9, 29.0, 29.1, 29.2, 29.4, 31.9, 33.3, 33.7, 34.7, 35.3, 38.3, 39.2, 39.8, 40.1, 40.9, 41.0, 41.4, 41.8, 42.2, 42.6, 42.9, 43.2, 44.6, 45.0, 47.1, 47.3, 119.7, 119.8, 128.2, 128.3, 128.4, 128.5, 131.1, 131.2, 143.8, 144.2, 144.5, 164.5, 167.2, 170.0, 170.3, 171.1; IR (neat, cm^{-1}) 3447, 2949, 2854,

2814, 2769, 1632, 1488, 1446, 1378, 1263, 1216, 1142, 1101, 1073, 1009, 958, 875, 814; HRMS (EI) *m/z* calcd. for $C_{19}H_{28}BrN_3O$ 393.14 [M^+]; found: 393.1421.



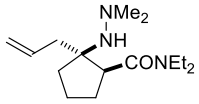
(*E*)-2-(2,2-dimethylhydrazono)-*N,N*-diethyl-4,4-dimethylcyclohexanecarboxamide (**1v**); yellow oil was obtained in 26%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.66-0.82 (m, 6H), 0.86-0.98 (m, 6H), 1.04-1.22 (m, 1H), 1.56-1.89 (m, 3H), 2.13-2.20 (m, 7H), 2.40 (t, *J* = 13.8 Hz, 1H), 2.96 (m, 1H), 3.11-3.39 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.3, 12.5, 14.0, 14.4, 24.8, 25.5, 25.6, 28.0, 28.6, 31.6, 33.3, 33.7, 35.0, 36.2, 38.6, 39.4, 39.9, 40.0, 41.2, 41.3, 46.0, 46.3, 47.2, 47.3, 167.5, 169.3, 170.2, 170.9; IR (neat, cm^{-1}) 3298, 2954, 2863, 2816, 2772, 1711, 1639, 1459, 1380, 1364, 1255, 1219, 1153, 1133, 1098, 1021, 969, 874, 799; HRMS (EI) *m/z* calcd. $C_{15}H_{29}N_3O$ 267.2311 [M^+]; found: 267.2323.

Allylation of Hydrazone and Dicarbonyl Compound: To a suspension of $ZnCl_2$(0.33 mmol, 45.0) in Et_2O(1.0 ml), allylmagnesium bromide (0.66 mmol, 1.0M in Et_2O) was added at 0 °C. After stirring for 1 h, a solution of compound **1f**(0.3 mmol, 71.8 mg) of toluene(1.5 ml) was added at room temperature and stirred for 15 h. Reaction mixture was quenched with a sat. NH_4Cl. The aqueous layer was separated and extracted with AcOEt and dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane / AcOEt = 3 / 1) to give the **4f** (72.5 mg, 0.26 mmol) in 86% yield.

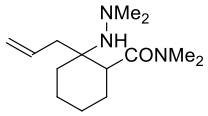


2-Allyl-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclohexanecarboxamide **4f**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.10 (t, *J* = 6.9 Hz, 3H), 1.15-1.24 (m, 5H), 1.34-1.45 (m, 2H), 1.71-1.75 (m, 1H), 1.87-1.99 (m, 2H), 2.01-2.12 (m, 1H), 2.27 (dd, *J* = 8.9, 13.7 Hz, 1H), 2.45 (s, 6H), 2.60 (dd, *J* = 6.4, 13.8 Hz, 1H), 3.16-3.41 (m, 4H), 4.57 (br, 1H), 4.96-5.06 (m, 2H), 5.79-5.90 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ

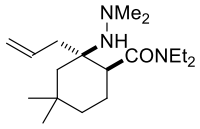
12.8, 14.4, 21.5, 25.6, 25.9, 32.0, 39.8, 42.1, 42.3, 44.8, 50.7, 60.2, 117.0, 136.2, 175.0; IR (neat, cm^{-1}) 3275, 3072, 2936, 2850, 2810, 2767, 1628, 1446, 1379, 1357, 1262, 1238, 1218, 1149, 1121, 1097, 989, 917, 836, 788, 732; (EI) *m/z* calcd. for $C_{16}H_{31}N_3O$ 281.2467 [M^+]; found: 281.2469.



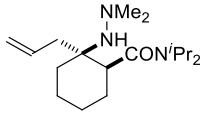
2-Allyl-2-(2,2-dimethylhydrazinyl)-*N,N*-diethylcyclopentanecarboxamide **4h** (24.8 mg, 0.09 mmol) was obtained in 31% yield; colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ 1.10 (t, *J* = 7.3 Hz, 3H), 1.16 (t, *J* = 7.3 Hz, 3H), 1.48-1.63 (m, 2H), 1.80-1.96 (m, 3H), 1.98-2.04 (m, 1H), 2.36-2.42 (m, 7H), 2.49 (dd, *J* = 6.8, 13.7 Hz, 1H), 2.71 (t, *J* = 8.7 Hz, 1H), 3.21-3.40 (m, 4H), 3.71 (br, 1H), 5.01-5.05 (m, 2H), 5.85-5.98 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 14.5, 21.7, 28.2, 35.0, 40.0, 40.2, 42.0, 46.2, 50.5, 70.4, 116.7, 136.3, 174.3; IR (neat, cm^{-1}) 3478, 3073, 2972, 2810, 2767, 1678, 1628, 1432, 1379, 1361, 1314, 1259, 1219, 1139, 1096, 998, 911; HRMS (EI) *m/z* calcd. for $C_{15}H_{29}N_3O$ 267.2311 [M^+]; found: 267.2315.



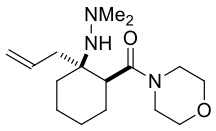
2-Allyl-2-(2,2-dimethylhydrazinyl)-*N,N*-dimethylcyclohexanecarboxamide **4e** (48.6 mg, 0.19 mmol) was obtained in 64% yield; colorless oil; ^1H NMR (400 MHz, $CDCl_3$) (major) δ 1.12-1.28 (m, 2H), 1.35-1.45 (m, 2H), 1.71-1.75 (m, 1H), 1.79-2.03 (m, 3H), 2.22-2.29 (m, 1H), 2.48-2.61 (m, 8H), 2.91 (s, 3H), 2.97 (s, 3H), 4.92-5.05 (m, 2H), 5.73-5.87 (m, 1H); (minor) δ 1.12-1.28 (m, 2H), 1.35-1.45 (m, 2H), 1.71-1.75 (m, 1H), 1.79-2.03 (m, 3H), 2.22-2.29 (m, 1H), 2.48-2.61 (m, 8H), 2.95 (s, 3H), 3.20 (s, 3H), 4.92-5.05 (m, 2H), 5.73-5.87 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) (major) δ 21.4, 24.5, 25.9, 31.8, 35.5, 37.5, 42.1, 44.5, 50.7, 60.4, 116.7, 136.3, 175.8; (minor) d 20.7, 25.3, 25.4, 35.2, 35.6, 37.2, 44.2, 50.7, 71.7, 117.1, 134.7, 177.0; IR (neat, cm^{-1}) 3452, 3276, 3071, 2938, 2851, 2810, 2767, 1637, 1483, 1445, 1416, 1398, 1352, 1259, 1154, 1119, 1047, 999, 915, 893, 733; HRMS (EI) *m/z* calcd. for $C_{14}H_{27}N_3O$ 253.2154 [M^+]; found: 253.2142.



2-Allyl-2-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-4,4-dimethylcyclohexanecarboxamide **4v** (19.5 mg, 0.06 mmol) was obtained in 21% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.98 (s, 3H), 1.08-1.12 (m, 4H), 1.16-1.20 (m, 6H), 1.37-1.66 (m, 3H), 1.77 (d, *J* = 13.7 Hz, 1H), 1.97-2.05 (m, 1H), 2.29 (dd, *J* = 8.2, 13.7 Hz, 1H), 2.40 (d, *J* = 10.0 Hz, 1H), 2.45 (s, 6H), 2.59 (dd, *J* = 6.4, 13.7 Hz, 1H), 3.18-3.27 (m, 1H), 3.31-3.39 (m, 3H), 5.00 (dd, *J* = 9.6, 17.0 Hz, 1H), 5.82-5.92 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 14.4, 23.0, 29.7, 30.6, 30.8, 33.3, 39.0, 39.9, 42.4, 42.7, 43.1, 44.7, 50.8, 60.8, 117.0, 136.6, 174.9; IR (neat, cm^{-1}) 3415, 2944, 2810, 2768, 1725, 1630, 1460, 1379, 1358, 1251, 1217, 1130, 1096, 911, 668; HRMS (ESI-TOF) *m/z* calcd. for $C_{18}H_{35}N_3NaO$ 332.2678 [$M+Na^+$]; found: 332.2689.

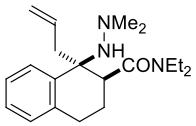


2-Allyl-2-(2,2-dimethylhydrazinyl)-*N,N*-diisopropylcyclohexanecarboxamide **4w** (71.4 mg, 0.23 mmol) was obtained in 77% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.15-1.23 (m, 8H), 1.25-1.31 (m, 1H), 1.35-1.41 (m, 7H), 1.69-1.72 (m, 1H), 1.85-1.97 (m, 2H), 1.98-2.08 (m, 1H), 2.34-2.50 (m, 8H), 2.57 (dd, *J* = 6.4, 13.7 Hz, 1H), 3.27-3.33 (m, 1H), 3.85-3.93 (m, 1H), 4.65 (br, 1H), 4.98-5.03 (m, 2H), 5.75-5.88 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5, 20.6, 20.7, 21.2, 21.6, 25.1, 26.0, 32.0, 42.0, 45.6, 48.7, 50.7, 60.4, 116.9, 136.3, 174.5; IR (neat, cm^{-1}) 3276, 3072, 2936, 2850, 2810, 2767, 1627, 1442, 1370, 1239, 1209, 1155, 1119, 1039, 993, 911, 863, 824, 779, 730; HRMS (EI) *m/z* calcd. for $C_{18}H_{35}N_3O$ 309.2780 [M^+]; found: 309.2772.

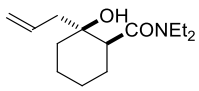


(2-Allyl-2-(2,2-dimethylhydrazinyl)cyclohexyl)(morpholino)methanone **4x** (71.7 mg, 0.24 mmol) was obtained in 81% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ

1.16-1.21 (m, 2H), 1.30-1.34 (m, 1H), 1.41-1.44 (m, 1H), 1.70-1.73 (m, 1H), 1.85-2.05 (m, 3H), 2.28 (dd, *J* = 9.2, 13.3 Hz, 1H), 2.45-2.51 (m, 7H), 2.60 (dd, *J* = 6.0, 13.3 Hz, 1H), 3.35-3.45 (m, 2H), 3.52-3.66 (m, 6H), 5.00 (dd, *J* = 10.0, 17.0 Hz, 2H), 5.75-5.86 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.3, 24.9, 25.8, 31.7, 41.4, 42.1, 44.0, 46.2, 50.6, 60.0, 66.6, 66.8, 117.0, 136.1, 174.3; IR (neat, cm^{-1}) 3423, 2946, 2852, 2803, 2762, 2104, 1636, 1457, 1361, 1270, 1221, 1113, 1038, 983, 920; HRMS (EI) *m/z* calcd. for $C_{16}H_{29}N_3O_2$ 295.2260 [M^+]; found: 295.2262.

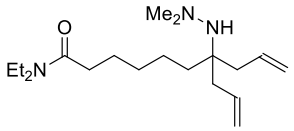


1-Allyl-1-(2,2-dimethylhydrazinyl)-*N,N*-diethyl-1,2,3,4-tetrahydronaphthalene-2-carbox amide **4y** (52.3 mg, 0.16 mmol) was obtained in 53% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.14 (t, *J* = 7.3 Hz, 3H), 1.71-2.49 (m, 8H), 2.58-2.68 (m, 1H), 2.83-2.91 (m, 2H), 3.01-3.07 (m, 1H), 3.14-3.52 (m, 4H), 3.63 (d, *J* = 13.7 Hz, 1H), 4.89 (br, 1H), 4.97 (dd, *J* = 10.0, 17.0 Hz, 1H), 5.62-5.65 (m, 1H), 7.09-7.15 (m, 3H), 7.60 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 14.4, 22.1, 28.7, 38.8, 40.1, 42.5, 42.6, 49.8, 61.4, 117.0, 124.5, 126.2, 127.9, 128.8, 136.4, 136.6, 139.2, 174.8; IR (neat, cm^{-1}) 3270, 3070, 2974, 2936, 2809, 2766, 1626, 1447, 1379, 1258, 1217, 1137, 1095, 1009, 965, 909, 845, 754; HRMS (EI) *m/z* calcd. for $C_{20}H_{31}N_3O$ 329.2467 [M^+]; found: 329.2496.

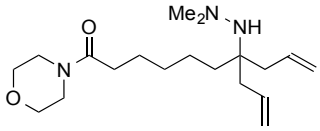


2-Allyl-*N,N*-diethyl-2-hydroxycyclohexanecarboxamide **4C** (68.8 mg, 0.29 mmol) was obtained in 96% yield; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.13 (t, *J* = 7.3 Hz, 3H), 1.16-1.23 (m, 5H), 1.50-1.53 (m, 2H), 1.71-1.84 (m, 3H), 1.94 (q, *J* = 13.3 Hz, 1H), 2.14 (dd, *J* = 8.7, 13.7 Hz, 1H), 2.28 (dd, *J* = 6.0, 13.7 Hz, 1H), 2.37 (d, *J* = 12.4 Hz, 1H), 3.23-3.47 (m, 4H), 4.82 (br, 1H), 5.02 (dd, *J* = 10.0, 17.4 Hz, 2H), 5.81-5.92 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 14.7, 20.7, 25.3, 26.4, 35.5, 40.1, 42.2, 44.8, 47.2, 71.5, 117.3, 134.4, 176.2; IR (neat, cm^{-1}) 3378, 3073, 2934, 2858, 1609, 1446, 1380, 1347, 1274, 1216, 1154, 1128, 1079, 983, 959, 913, 835, 790; HRMS

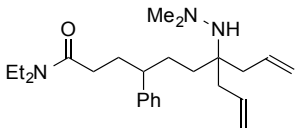
(ESI-TOF) *m/z* calcd. for $C_{14}H_{25}NNaO_2$ 262.1783 [M+Na$^+$]; found: 262.1781.



7-Allyl-7-(2,2-dimethylhydrazinyl)-*N*,*N*-diethyldec-9-enamide **5f** (66.9 mg, 0.20 mmol) was obtained in 69% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.11 (t, *J* = 7.3 Hz, 3H), 1.17 (t, *J* = 7.3 Hz, 3H), 1.25-1.37 (m, 6H), 1.61-1.67 (m, 2H), 2.01-2.08 (m, 2H), 2.12-2.22 (m, 3H), 2.28 (t, *J* = 8.2 Hz, 2H), 2.41 (s, 6H), 3.30 (t, *J* = 6.8 Hz, 2H), 3.37 (t, *J* = 6.8 Hz, 2H), 4.92-5.08 (m, 2H), 5.75-5.90 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.1, 14.4, 22.9, 25.4, 30.2, 33.1, 35.2, 40.0, 40.1, 41.9, 50.8, 60.0, 117.2, 134.9, 172.2; IR (neat, cm^{-1}) 3446, 3075, 2934, 1709, 1637, 1459, 1379, 1264, 1219, 1141, 1097, 996, 912; HRMS (ESI-TOF) *m/z* calcd. for $C_{19}H_{37}N_3NaO$ 346.2834 [M+Na$^+$]; found: 346.2835.

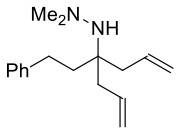


7-Allyl-7-(2,2-dimethylhydrazinyl)-1-morpholinodec-9-en-1-one **5x** (56.7 mg, 0.18 mmol) was obtained in 61% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.18-1.32 (m, 6H), 1.53-1.60 (m, 2H), 1.75 (br, 1H), 2.05-2.16 (m, 4H), 2.23 (t, *J* = 8.2 Hz, 2H), 2.34 (s, 6H), 3.38-3.40 (m, 2H), 3.54-3.56 (m, 2H), 3.59-3.61 (m, 4H), 4.95-5.02 (m, 4H), 5.72-5.82 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.9, 25.2, 30.1, 33.1, 35.2, 40.1, 41.8, 46.0, 50.8, 60.0, 66.7, 66.9, 117.3, 134.8, 171.8; IR (neat, cm^{-1}) 3451, 3072, 2936, 2854, 2768, 1646, 1431, 1362, 1299, 1271, 1230, 1116, 1069, 1031, 912; HRMS (ESI-TOF) *m/z* calcd. for $C_{19}H_{36}N_3O_2$ 338.2808 [M+H$^+$]; found: 338.2804.



7-Allyl-7-(2,2-dimethylhydrazinyl)-*N*,*N*-diethyl-4-phenyldec-9-enamide **5n** (59.9 mg, 0.15 mmol) was obtained in 51% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.97 (t, *J* = 7.3 Hz, 3H), 1.06 (t, *J* = 6.9 Hz, 3H), 1.10-1.17 (m, 1H), 1.24-1.39 (m, 2H),

1.46-1.71 (m, 2H), 1.78-1.87 (m, 1H), 2.04-2.18 (m, 2H), 2.34 (s, 6H), 2.41-2.50 (m, 1H), 2.98-3.12 (m, 2H), 3.25-3.38 (m, 2H), 4.92-5.06 (m, 4H), 5.64-5.84 (m, 2H), 7.12-7.19 (m, 3H), 7.25-7.29 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 14.1, 30.6, 31.0, 31.9, 33.4, 39.9, 41.7, 46.3, 50.7, 59.9, 117.2, 117.3, 126.1, 127.6, 128.3, 134.6, 134.7, 145.0, 171.9; IR (neat, cm^{-1}) 3751, 3441, 2977, 2810, 2767, 2086, 1638, 1509, 1450, 1378, 1262, 1221, 1139, 1095, 996, 908, 732, 701; HRMS (ESI-TOF) *m/z* calcd. for $C_{25}H_{41}N_3NaO$ 422.3147 [M+Na$^+$]; found: 422.3165.



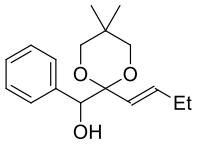
1,1-Dimethyl-2-(4-phenethylhepta-1,6-dien-4-yl)hydrazine **5h** (43.3 mg, 0.16 mmol) was obtained in 56% yiled; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.59-1.63 (m, 2H), 2.14-2.26 (m, 4H), 2.38 (s, 6H), 2.53-2.58 (m, 2H), 5.02-5.08 (m, 4H), 5.78-5.88 (m, 2H), 7.06-7.13 (m, 3H), 7.17-7.21 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 29.7, 37.7, 40.1, 50.8, 60.1, 117.6, 125.6, 128.3, 128.4, 134.6, 143.0; IR (neat, cm^{-1}) 3073, 3025, 2944, 2847, 2810, 2767, 1831, 1718, 1637, 1603, 1495, 1452, 1294, 1147, 995, 912, 746, 699; HRMS (ESI-TOF) *m/z* calcd. for $C_{17}H_{26}N_2Na$ 281.1994 [M+Na$^+$]; found: 281.1990.

Chapter 2

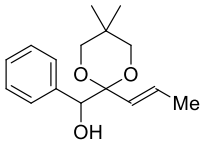
General Procedure

To a solution of **L1** (18.0 mg, 0.075 mmol) in toluene (3.0 mL), Et_2Zn (0.39 mL, 1.0 M in toluene) was added at room temperature. After stirring for 10 min, CPA (54.6 μL, 0.39 mmol) and benzaldehyde **6a** (30.6 μL, 0.3 mmol) were added at room temperature and stirred for 21 h. Reaction mixture was quenched with a sat. NH_4Cl aq. The aqueous layer was separated and extracted with AcOEt and dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane / AcOEt = 10 / 1) to give the **7a** (62.8 mg, 0.23 mmol) in 76% yield.

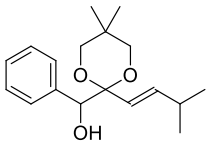
Products **7** were sometimes obtained as a *E*/*Z* mixture; the ratio was typically >10/1. We showed the chemical shift of major (*E*)-isomers in NMR analyses, since we could not exactly identify the chemical shift of minor (*Z*)-isomers.



(*E*)-(2-(But-1-enyl)-5,5-dimethyl-1,3-dioxan-2-yl)(phenyl)methanol **7a**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 3H), 0.94 (t, *J* = 7.8 Hz, 3H), 1.16 (s, 3H), 2.03–2.10 (m, 2H), 3.02 (d, *J* = 3.2 Hz, 1H), 3.33–3.38 (m, 2H), 3.59 (t, *J* = 12.0 Hz, 2H), 4.58 (d, *J* = 3.2 Hz, 1H), 4.98 (d, *J* = 16.0 Hz, 1H), 5.65 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.22–7.29 (m, 3H), 7.36–7.37 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 22.0, 22.9, 25.2, 30.3, 71.2, 71.3, 79.7, 100.4, 124.3, 127.2, 127.4, 128.5, 138.4, 139.5; IR (neat, cm^{-1}) 3479, 3031, 2956, 2871, 1729, 1453, 1394, 1195, 1159, 1123, 1064, 1019, 991, 700; HRMS (EI) *m/z* calcd. $C_{17}H_{24}O_3$ 276.1725 [M^+]; found: 276.1743.

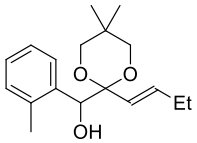


(*E*)-(5,5-Dimethyl-2-(prop-1-en-1-yl)-1,3-dioxan-2-yl)(phenyl)methanol **7a-Me** (37.7 mg, 0.14 mmol) was obtained in 48% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 3H), 1.14 (s, 3H), 1.72 (d, *J* = 6.4 Hz, 3H), 2.80 (br, 1H), 3.32–3.37 (m, 2H), 3.59 (dd, *J* = 6.8, 11.4 Hz, 2H), 4.57 (s, 1H), 5.04 (d, *J* = 16.0 Hz, 1H), 5.64 (dq, *J* = 16.0, 6.4 Hz, 1H), 7.22–7.38 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 17.7, 21.9, 22.8, 30.3, 71.2, 71.3, 79.6, 100.3, 126.8, 127.1, 127.4, 128.4, 132.8, 138.5; IR (neat, cm^{-1}) 3449, 3031, 2954, 2870, 1686, 1671, 1629, 1542, 1509, 1496, 1452, 1395, 1320, 1239, 1196, 1160, 1107, 1061, 1017, 991, 940, 833, 753, 700; HRMS (ESI-TOF) *m/z* calcd. $C_{16}H_{22}NaO_3$ 285.1467 [M+Na^+]; found: 285.1464.

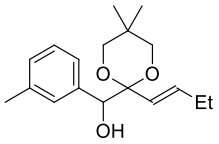


(*E*)-(5,5-Dimethyl-2-(3-methylbut-1-en-1-yl)-1,3-dioxan-2-yl)(phenyl)methanol **7a-*i*-Pr**

(48.7 mg, 0.17 mmol) was obtained in 56% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 3H), 0.95 (d, *J* = 6.9 Hz, 6H), 1.18 (s, 3H), 2.25–2.36 (m, 1H), 3.04 (br, 1H), 3.33–3.38 (m, 2H), 3.59 (t, *J* = 8.7 Hz, 2H), 4.58 (s, 1H), 4.93 (d, *J* = 16.0 Hz, 1H), 5.57 (dd, *J* = 16.0, 6.9 Hz, 1H), 7.21–7.29 (m, 3H), 7.36–7.38 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.0, 22.1, 22.9, 30.3, 30.8, 71.2, 71.3, 79.7, 100.4, 122.2, 127.1, 127.4, 128.5, 138.4, 144.9; IR (neat, cm^{-1}) 3448, 3032, 2955, 2868, 2029, 1618, 1496, 1467, 1394, 1363, 1238, 1196, 1122, 1063, 1021, 754, 701; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO_3$ 313.1779 [M+Na^+]; found: 313.1778.

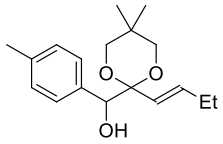


(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(*o*-tolyl)methanol **7b** (53.9 mg, 0.19 mmol) was obtained in 62% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 3H), 0.96 (t, *J* = 7.3 Hz, 3H), 1.17 (s, 3H), 2.04–2.11 (m, 2H), 2.33 (s, 3H), 2.91 (br, 1H), 3.30–3.38 (m, 2H), 3.60 (dd, *J* = 4.6, 10.6 Hz, 2H), 4.92 (s, 1H), 5.05 (d, *J* = 16.0 Hz, 1H), 5.67 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.06–7.08 (m, 1H), 7.11–7.17 (m, 2H), 7.47–7.51 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 20.1, 21.9, 22.8, 25.2, 30.3, 71.1, 71.2, 74.9, 101.2, 123.9, 125.0, 127.2, 128.3, 129.5, 136.7, 137.1, 139.5; IR (neat, cm^{-1}) 3448, 2955, 2870, 1664, 1628, 1465, 1394, 1159, 1114, 1072, 1051, 1018, 992, 944, 906, 729; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO_3$ 313.1780 [M+Na^+]; found: 313.1777.

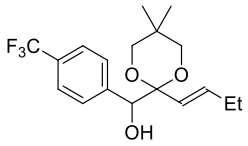


(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(*m*-tolyl)methanol **7c** (59.2 mg, 0.20 mmol) was obtained in 68% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 0.96 (t, *J* = 7.8 Hz, 3H), 1.18 (s, 3H), 2.04–2.11 (m, 2H), 2.33 (s, 3H), 3.00 (d, *J* = 3.6 Hz, 1H), 3.33–3.38 (m, 2H), 3.60 (dd, *J* = 8.2, 11.0 Hz, 2H), 4.55 (d, *J* = 3.6 Hz, 1H), 4.99 (d, *J* = 16.0 Hz, 1H), 5.68 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.04–7.06 (m, 1H), 7.16 (d, *J* = 5.0 Hz, 2H), 7.19 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 21.4, 22.0, 22.9, 25.2, 30.3, 71.3, 71.4, 79.7, 100.5, 124.5, 125.6, 127.1, 128.2, 129.2, 136.6, 138.4,

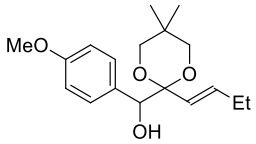
139.4; IR (neat, cm^{-1}) 3474, 2956, 2870, 1664, 1609, 1467, 1393, 1363, 1316, 1240, 1158, 1123, 1074, 1020, 907, 709; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO_3$ 313.1780 [M+Na^+]; found: 313.1775.



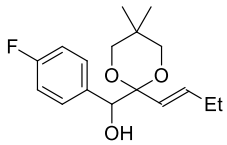
(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(*p*-tolyl)methanol **7d** (61.8 mg, 0.21 mmol) was obtained in 71% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 3H), 0.97 (t, *J* = 7.8 Hz, 3H), 1.17 (s, 3H), 2.04–2.12 (m, 2H), 2.32 (s, 3H), 2.98 (d, *J* = 3.2 Hz, 1H), 3.31–3.38 (m, 2H), 3.59 (t, *J* = 9.2 Hz, 2H), 4.54 (d, *J* = 3.2 Hz, 1H), 4.98 (d, *J* = 16.0 Hz, 1H), 5.68 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.08 (d, *J* = 8.2 Hz, 2H), 7.25 (d, *J* = 7.8 Hz, 2H) ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 21.1, 22.0, 22.9, 25.2, 30.3, 71.2, 71.3, 79.6, 100.4, 124.4, 127.9, 128.3, 135.4, 136.9, 139.4; IR (neat, cm^{-1}) 3481, 2956, 2870, 1665, 1515, 1468, 1392, 1320, 1239, 1159, 1123, 1077, 1019, 992, 907, 819, 766; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO_3$ 313.1780 [M+Na^+]; found: 313.1778.



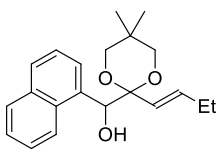
(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(4-(trifluoromethyl)phenyl)methanol **7e** (72.2 mg, 0.21 mmol) was obtained in 70% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 0.95 (t, *J* = 7.3 Hz, 3H), 1.14 (s, 3H), 2.03–2.12 (m, 2H), 3.10 (br, 1H), 3.33–3.37 (m, 2H), 3.59 (dd, *J* = 6.0, 11.0 Hz, 2H), 4.64 (s, 1H), 4.97 (d, *J* = 16.0 Hz, 1H), 5.64 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.48–7.54 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 21.9, 22.8, 25.2, 30.3, 71.2, 71.4, 79.1, 100.1, 123.8, 124.0 (q, *J* = 3.8 Hz, 2 carbons overlapped), 128.8, 129.2 (q, *J* = 42.0 Hz), 140.1, 142.5; ^{19}F NMR (376 MHz, $CDCl_3$) δ –62.29; IR (neat, cm^{-1}) 3482, 2959, 2872, 1923, 1733, 1665, 1620, 1560, 1470, 1416, 1394, 1364, 1325, 1240, 1123, 1067, 1019, 907, 845, 826, 790, 761, 695; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}F_3NaO_3$ 367.1497 [M+Na^+]; found: 367.1492.



(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(4-methoxyphenyl)methanol **7f** (51.4 mg, 0.17 mmol) was obtained in 56% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.60 (s, 3H), 0.89 (t, *J* = 7.8 Hz, 3H), 1.09 (s, 3H), 1.96–2.04 (m, 2H), 3.25–3.30 (m, 2H), 3.52 (dd, *J* = 8.2, 11.0 Hz, 2H), 3.71 (s, 3H), 4.46 (s, 1H), 4.91 (d, *J* = 16.0 Hz, 1H), 5.59 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.74 (d, *J* = 8.7 Hz, 2H), 7.22 (d, *J* = 8.7 Hz, 2H), OH proton was not observed clearly; ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 22.0, 22.9, 25.2, 30.3, 55.1, 71.2, 71.3, 79.3, 100.5, 112.6, 124.4, 129.5, 130.7, 139.4, 158.9; IR (neat, cm^{-1}) 3462, 2956, 2870, 1734, 1614, 1513, 1465, 1394, 1301, 1248, 1160, 1123, 1075, 1021, 992, 826; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO_4$ 329.1729 [M+Na^+]; found: 329.1727.

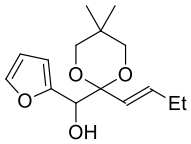


(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(4-fluorophenyl)methanol **7g** (45.2, 0.15 mmol) was obtained in 52% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 0.96 (t, *J* = 7.3 Hz, 3H), 1.15 (s, 3H), 2.03–2.11 (m, 2H), 3.32–3.37 (m, 2H), 3.59 (dd, *J* = 7.3, 11.0 Hz, 2H), 4.56 (s, 1H), 4.97 (d, *J* = 16.0 Hz, 1H), 5.64 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.96 (d, *J* = 8.7 Hz, 2H), 7.34 (dd, *J* = 5.5, 8.7 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 21.9, 22.8, 25.2, 30.3, 71.2, 71.3, 79.0, 100.3, 114.0 (d, *J* = 21.0 Hz), 124.1, 130.0 (d, *J* = 7.6 Hz), 134.2, 139.8, 162.3 (d, *J* = 244 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –115.48; IR (neat, cm^{-1}) 3474, 2955, 2870, 1665, 1604, 1509, 1471, 1391, 1364, 1313, 1220, 1194, 1157, 1123, 1076, 1016, 992, 943, 906, 880, 839, 778; HRMS (ESI-TOF) *m/z* calcd. $C_{17}H_{23}FNaO_3$ 317.1529 [M+Na^+]; found: 317.1528.

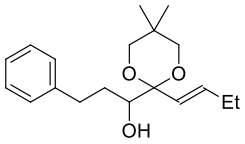


(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(naphthalen-1-yl)methanol **7h**

(46.7 mg, 0.14 mmol) was obtained in 48% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.66 (s, 3H), 0.79 (t, *J* = 7.3 Hz, 3H), 1.24 (s, 3H), 1.90–2.00 (m, 2H), 3.21 (d, *J* = 3.2 Hz, 1H), 3.31–3.41 (m, 2H), 3.58–3.62 (m, 2H), 4.98 (d, *J* = 16.0 Hz, 1H), 5.53 (d, *J* = 3.2 Hz, 1H), 5.63 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.39–7.50 (m, 3H), 7.72–7.81 (m, 3H), 8.16 (d, *J* = 7.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 21.9, 22.9, 25.1, 30.3, 71.3 (2 carbons overlapped), 74.8, 101.2, 124.0, 124.8 (3 carbons overlapped), 125.2, 126.6, 128.0, 128.3, 132.1, 133.3, 134.7, 139.7; IR (neat, cm^{-1}) 3474, 3048, 2956, 2869, 1665, 1596, 1511, 1468, 1392, 1363, 1217, 1159, 1123, 1087, 1019, 983, 907, 865, 778, 732; HRMS (ESI-TOF) *m/z* calcd. $C_{21}H_{26}NaO_3$ 349.1780 [M+Na^+]; found: 349.1778.

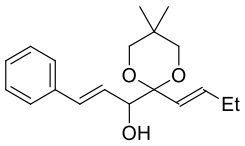


(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(furan-2-yl)methanol **7j** (59.2 mg, 0.22 mmol) was obtained in 74% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.69 (s, 3H), 0.98 (t, *J* = 7.8 Hz, 3H), 1.17 (s, 3H), 2.07–2.14 (m, 2H), 2.91 (d, *J* = 5.5 Hz, 1H), 3.38–3.44 (m, 2H), 3.65 (dd, *J* = 3.7, 11.0 Hz, 2H), 4.59 (d, *J* = 5.5 Hz, 1H), 5.16 (d, *J* = 16.0 Hz, 1H), 5.82 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.30–6.34 (m, 2H), 7.37 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.3, 22.0, 22.8, 25.2, 30.3, 71.3, 71.4, 74.1, 100.0, 108.5, 110.1, 124.2, 139.8, 141.7, 152.3; IR (neat, cm^{-1}) 3463, 2957, 2871, 1719, 1664, 1500, 1468, 1396, 1364, 1151, 1073, 1018, 926, 885, 732; HRMS (ESI-TOF) *m/z* calcd. $C_{15}H_{22}NaO_4$ 289.1416 [M+Na^+]; found: 289.1410.

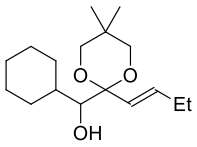


(*E*)-1-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-3-phenylpropan-1-ol **7k** (66.6 mg, 0.23 mmol) was obtained in 73% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 1.02 (t, *J* = 7.3 Hz, 3H), 1.18 (s, 3H), 1.68–1.78 (m, 1H), 1.84–1.92 (m, 1H), 2.10–2.17 (m, 2H), 2.45 (d, *J* = 2.8 Hz, 1H), 2.59–2.67 (m, 1H), 2.88–2.97 (m, 1H), 3.30–3.37 (m, 2H), 3.47 (d, *J* = 11.4 Hz, 1H), 3.63 (dd, *J* = 7.4, 10.5 Hz, 2H), 5.20 (d, *J* = 16.0 Hz, 1H), 5.83 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.14–7.28 (m, 5H); ^{13}C NMR (100 MHz,

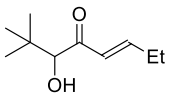
$CDCl_3$) δ 13.4, 22.0, 23.0, 25.3, 30.4, 31.8, 32.5, 71.1, 71.2, 76.8, 100.4, 124.7, 125.6, 128.2, 128.5, 139.4, 142.5; IR (neat, cm^{-1}) 3482, 3026, 2956, 2869, 1734, 1654, 1469, 1457, 1396, 1123, 1094, 1017, 748, 699; HRMS (ESI-TOF) *m/z* calcd. $C_{19}H_{28}NaO_3$ 327.1936 [M+Na^+]; found: 327.1930.



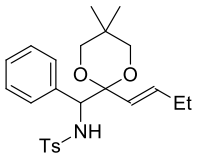
(*E*)-1-(2-((*E*)-But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-3-phenylprop-2-en-1-ol **7l** (61.4 mg, 0.20 mmol) was obtained in 68% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.70 (s, 3H), 1.02 (t, *J* = 7.3 Hz, 3H), 1.22 (s, 3H), 2.11–2.19 (m, 2H), 2.63 (d, *J* = 4.2 Hz, 1H), 3.36–3.41 (m, 2H), 3.62–3.69 (m, 2H), 4.14–4.17 (m, 1H), 5.24 (d, *J* = 16.0 Hz, 1H), 5.89 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.29 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.62 (d, *J* = 16.0 Hz, 1H), 7.20 (t, *J* = 5.0 Hz, 1H), 7.29 (t, *J* = 7.4 Hz, 2H), 7.38 (d, *J* = 7.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.5, 22.0, 23.0, 25.3, 30.4, 71.3 (2 carbons overlapped), 78.1, 100.5, 124.7, 126.4, 126.5, 127.3, 128.4, 132.4, 137.1, 139.8; IR (neat, cm^{-1}) 3854, 3448, 2956, 1654, 1458, 1389, 1164, 1120, 1070, 1019, 971, 748; HRMS (ESI-TOF) *m/z* calcd. $C_{19}H_{26}NaO_3$ 325.1780 [M+Na^+]; found: 325.1781.



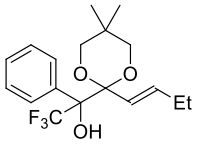
(*E*)-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(cyclohexyl)methanol **7m** (65.1 mg, 0.23 mmol) was obtained in 77% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 1.05 (t, *J* = 7.8 Hz, 3H), 1.09–1.33 (m, 8H), 1.57–1.72 (m, 5H), 1.91–1.94 (m, 1H), 2.12–2.20 (m, 2H), 2.40 (d, *J* = 4.6 Hz, 1H), 3.24 (s, 1H), 3.30–3.36 (m, 2H), 3.63 (d, *J* = 10.1 Hz, 2H), 5.25 (d, *J* = 16.0 Hz, 1H), 5.85 (dt, *J* = 16.0, 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.4, 22.1, 23.0, 25.4, 26.3, 26.4, 26.7, 27.3, 30.3, 31.6, 38.5, 71.0, 71.1, 81.2, 101.1, 125.4, 138.6; IR (neat, cm^{-1}) 3510, 2922, 2851, 1664, 1451, 1395, 1363, 1261, 1140, 1113, 1069, 1019, 988, 951, 892; HRMS (ESI-TOF) *m/z* calcd. $C_{17}H_{30}NaO_3$ 305.2093 [M+Na^+]; found: 305.2092.



(*E*)-3-hydroxy-2,2-dimethyloct-5-en-4-one **7n** (17.7 mg, 0.11 mmol) was obtained in 35% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.90 (s, 9H), 1.02 (t, *J* = 7.3 Hz, 3H), 2.17–2.24 (m, 2H), 3.97 (s, 1H), 6.19 (d, *J* = 16.0 Hz, 1H), 7.00 (dt, *J* = 16.0, 6.0 Hz, 1H), OH proton was not observed clearly; ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.1, 25.7, 26.4, 36.1, 82.6, 126.9, 150.2, 201.4; IR (neat, cm^{-1}) 3449, 2965, 1685, 1623, 1509, 1458, 1366, 1338, 1287, 1059, 1020, 982; HRMS (ESI-TOF) *m/z* calcd. $C_{10}H_{18}NaO_2$ 193.1204 [M+Na^+]; found: 193.1186.

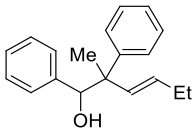


(*E*)-*N*-((2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)(phenyl)methyl)-4-methylbenzenesulfonamide **7o** (52.5 mg, 0.12 mmol) was obtained in 41% yield; white solid of mp = 119–120 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.60 (s, 3H), 0.90 (t, *J* = 7.8 Hz, 3H), 0.92 (s, 3H), 1.96–2.05 (m, 2H), 2.32 (s, 3H), 3.21 (d, *J* = 11.0 Hz, 2H), 3.49 (dd, *J* = 11.0, 21.5 Hz, 2H), 4.29 (d, *J* = 7.4 Hz, 1H), 4.91 (d, *J* = 16.0 Hz, 1H), 5.50 (d, *J* = 7.4 Hz, 1H), 5.68 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.04–7.15 (m, 7H), 7.49 (d, *J* = 8.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 21.4, 21.9, 22.8, 25.1, 30.0, 65.6, 71.2, 99.7, 125.1, 127.1, 128.8, 129.3, 136.8, 137.9, 139.6, 142.4; IR (neat, cm^{-1}) 3854, 3649, 3422, 2956, 1654, 1422, 1331, 1161, 1076, 1011, 918, 862, 811, 695, 668; HRMS (ESI-TOF) *m/z* calcd. $C_{24}H_{31}NNaO_4S$ 452.1871 [M+Na^+]; found: 452.1865.



(*E*)-1-(2-(But-1-en-1-yl)-5,5-dimethyl-1,3-dioxan-2-yl)-2,2,2-trifluoro-1-phenylethanol **7p** (28.9 mg, 0.08 mmol) was obtained in 28% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 0.80 (t, *J* = 7.8 Hz, 3H), 1.19 (s, 3H), 1.90–1.98 (m, 2H), 3.40–3.46 (m, 2H), 3.63 (dd, *J* = 4.1, 11.5 Hz, 2H), 3.89 (br, 1H), 4.85 (d, *J* = 16.0 Hz, 1H), 5.55 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.28–7.32 (m, 3H), 7.67–7.70 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 22.1, 22.8, 25.1, 30.2, 71.4, 71.7, 79.5, 91.6, 101.0, 122.7, 127.2,

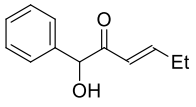
127.4, 128.0, 134.6, 141.1; ^{19}F NMR (376 MHz, $CDCl_3$) δ –70.59; IR (neat, cm^{-1}) 3584, 3440, 2961, 1644, 1453, 1403, 1329, 1262, 1236, 1128, 1062, 911, 876, 844, 759, 718; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{23}F_3NaO_3$ 367.1497 [M+Na^+]; found: 367.1493.



(*E*)-2-Methyl-1,2-diphenylhex-3-en-1-ol **9aa** (24.7 mg, 0.09 mmol) was obtained in 31% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 1.01 (t, *J* = 7.8 Hz, 3H), 1.24 (s, 3H), 1.79 (br, 1H), 2.11–2.18 (m, 2H), 5.03 (s, 1H), 5.50 (dt, *J* = 15.6, 6.4 Hz, 1H), 6.12 (d, *J* = 15.6 Hz, 1H), 7.08–7.39 (m, 10H); (minor) δ 0.94 (t, *J* = 7.3 Hz, 3H), 1.37 (s, 3H), 1.79 (br, 1H), 2.00–2.08 (m, 2H), 4.98 (s, 1H), 5.39 (dt, *J* = 15.6, 6.4 Hz, 1H), 5.82 (d, *J* = 15.6 Hz, 1H), 7.08–7.39 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.7, 13.8, 20.4, 21.3, 25.9, 26.1, 49.2, 49.4, 80.4, 80.5, 126.3, 126.4, 127.0, 127.1, 127.2, 127.3, 127.8, 127.9, 128.0, 128.1, 128.2, 132.1, 132.5, 133.1, 134.3, 140.1, 140.4, 144.5, 145.7; IR (neat, cm^{-1}) 3452, 3086, 3058, 3028, 2962, 2930, 2872, 1949, 1711, 1600, 1494, 1453, 1375, 1234, 1188, 1024, 982, 914, 763, 731, 700; HRMS (ESI-TOF) *m/z* calcd. $C_{19}H_{22}NaO$ 289.1568 [M+Na^+]; found: 289.1565.

Deprotection of Acetal Moiety

To the solution of **2a** (55.2 mg, 0.20 mmol) in acetone (2.0 mL), *p*-toluenesulfonic acid (3.5 mg, 0.02 mmol) was added at room temperature. After stirring for 30 min, sat. $NaHCO_3$ aq was added. The aqueous layer was extracted with $CHCl_3$ and dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane / AcOEt = 10 / 1) to give the product **3** (37 mg, 0.19 mmol) in 98% yield.



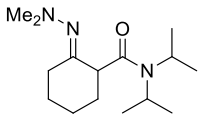
(*E*)-1-Hydroxy-1-phenylhex-3-en-2-one **10a**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.99 (t, *J* = 7.3 Hz, 3H), 2.14–2.21 (m, 2H), 4.51 (br, 1H), 5.22 (s, 1H), 6.11 (d, *J* = 16.0 Hz, 1H), 7.10 (dt, *J* = 16.0, 6.4 Hz, 1H), 7.31–7.40 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.9, 25.8, 78.5, 123.5, 127.7, 128.6, 129.0, 138.1, 152.2, 197.4; IR (neat, cm^{-1}) 3584, 3413, 2920, 1719, 1689, 1623, 1543, 1509, 1457, 1379, 1057, 976, 783, 739,

699; HRMS (ESI-TOF) *m/z* calcd. $C_{12}H_{14}NaO_2$ 213.0891 [M+Na^+]; found: 213.0889.

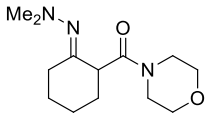
Synthesis of Ligand

Synthesis of L2 and L3

Hydrazone-amide **L2** and **L3** were preparated in our previous manner.[S1]



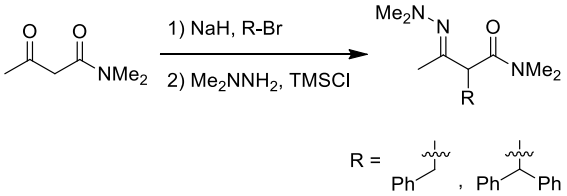
(*E*)-2-(2,2-Dimethylhydrazono)-*N*,*N*-diisopropylcyclohexanecarboxamide **L2** (694 mg, 2.6 mmol) was obtained in 52% yield ; colorless oil; a mixture of *E*/*Z* isomers of hydrazone; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.15–1.22 (m, 7H), 1.37–1.41 (m, 7H), 1.51–1.65 (m, 2H), 1.80–1.88 (m, 1H), 1.91–1.97 (m, 1H), 2.03–2.11 (m, 1H), 2.42–2.49 (m, 1H), 2.66 (br, 6H), 3.31–3.46 (m, 2H), 3.88–3.96 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.1, 20.2, 20.4, 20.6, 20.8, 20.9, 21.7, 23.4, 26.5, 27.3, 27.8, 29.6, 30.5, 33.9, 41.0, 45.5, 45.7, 47.3, 47.4, 47.9, 48.1, 49.0, 168.1, 169.9, 170.2, 170.8; IR (neat, cm^{-1}) 3482, 2962, 2857, 2817, 2772, 1712, 1636, 1441, 1371, 1327, 1289, 1213, 1155, 1135, 1078, 1041, 1021, 997, 968, 928, 882, 829, 770, 705; HRMS (EI) *m/z* calcd. for $C_{15}H_{29}N_3O$ 267.2311 [M^+]; found: 267.2319.



(*E*)-(2-(2,2-Dimethylhydrazono)cyclohexyl)(morpholino)methanone **L3** (481 mg, 1.9 mmol) was obtained in 38% yield ; colorless oil; a mixture of *E*/*Z* isomers of hydrazone; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31–1.57 (m, 3H), 1.74–2.01 (m, 3H), 2.22–2.26 (m, 1H), 2.28–2.32 (m, 6H), 2.69–2.75 (m, 1H), 3.23–3.29 (m, 2H), 3.36–3.40 (m, 2H), 3.45–3.62 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.6, 23.3, 26.0, 27.4, 27.6, 29.4, 29.8, 33.6, 39.6, 41.7, 42.1, 45.6, 45.9, 47.1, 47.3, 66.3, 66.5, 166.9, 169.3, 169.6, 170.3; IR (neat, cm^{-1}) 2839, 1666, 1454, 1299, 1250, 1113, 1002, 954, 904, 880, 851,

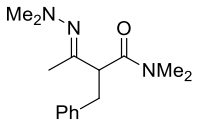
790, 705; HRMS (EI) *m/z* calcd. for $C_{13}H_{23}N_3O_2$ 253.1790 [M^+]; found: 253.1783.

Synthesis of L4 and L5



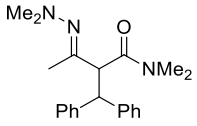
Synthesis of L4; To a suspension of sodium hydride (210 mg, 0.525 mmol, 60%) in THF (15 mL), *N*,*N*-dimethylacetoacetamide (646 mg, 5.0 mmol) was added at 0 °C. After stirring for 30 min, the whole was warmed at room temperature. Benzyl bromide (855 mg, 5.0 mmol) was added at room temperature and stirred overnight. The reaction mixture was quenched with a satd. NH_4Cl aq. The aqueous layer was separated and extracted with AcOEt. The combined organic layers were washed with H_2O, brine, and dried over Na_2SO_4. To the solution of α-benzyl ketoamide in 1,1-dimethylhydrazine (5 mL), trimethylsilyl chloride (1.57 mL, 10 mmol) was added and stirred for overnight at room temperature. The reaction mixture was quenched with sat. NH_4Cl aq. The organic layer was extracted with $CHCl_3$. The combined organic extracts were dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane / AcOEt = 1 / 1) to give the **L4** (1.18 g, 4.5 mmol) in 90% yield.

In similar manner, **L5** was prepared from *N*,*N*-dimethylacetoacetamide.



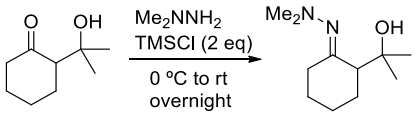
(*Z*)-2-Benzyl-3-(2,2-dimethylhydrazono)-*N*,*N*-dimethylbutanamide **L4**; yellow oil; a mixture of *E*/*Z* isomers of hydrazone; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 1.88 (s, 3H), 2.25 (s, 6H), 2.82 (d, *J* =14.2 Hz, 1H), 2.85 (s, 3H), 2.91 (s, 3H), 3.20 (dd, *J* = 7.8, 14.2 Hz, 1H), 3.79 (t, *J* = 7.8 Hz, 1H), 7.08–7.18 (m, 5H); (minor) d 1.96 (s, 3H), 2.29 (s, 6H), 2.87–2.89 (m, 4H), 2.93 (s, 3H), 3.40 (dd, *J* = 9.6, 13.8 Hz, 1H), 4.92 (dd, *J* = 4.6, 9.6 Hz, 1H), 7.08–7.18 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.6, 19.7, 27.4, 35.5, 35.7, 36.3, 36.9, 37.1, 45.6, 46.4, 47.1, 53.2, 125.9, 126.1, 127.9, 128.1, 128.2,

128.5, 128.8, 138.7, 164.5, 168.5, 169.6, 169.9; IR (neat, cm^{-1}) 3489, 3061, 3026, 2951, 2857, 2818, 2774, 1718, 1647, 1495, 1454, 1396, 1361, 1262, 1196, 1136, 1078, 1057, 1022, 960, 750, 701; HRMS (ESI-TOF) *m/z* calcd. for $C_{15}H_{23}N_3NaO$ 284.1739 [M+Na^+]; found: 284.1737.

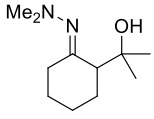


(*E*)-2-Benzhydryl-3-(2,2-dimethylhydrazono)-*N*,*N*-dimethylbutanamide **L5** (1.56 g, 4.3 mmol) was obtained in 87% yield; white solid of mp = 126-127 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.79 (s, 3H), 2.08 (s, 6H), 2.74 (s, 3H), 3.03 (s, 3H), 4.51 (d, *J* = 11.9 Hz, 1H), 4.74 (d, *J* = 11.9 Hz, 1H), 7.03–7.07 (m, 2H), 7.13–7.17 (m, 4H), 7.21–7.27 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 36.0, 37.4, 46.4, 51.3, 55.7, 126.3, 126.4, 127.5, 128.2, 128.4, 128.9, 141.5, 142.9, 169.0; IR (neat, cm^{-1}) 3416, 2960, 2921, 2861, 2818, 2774, 1628, 1394, 1353, 1270, 1197, 1135, 1089, 1021, 979, 955, 805, 754, 742, 701; HRMS (ESI-TOF) *m/z* calcd. for $C_{21}H_{27}N_3NaO$ 360.2052 [M+Na^+]; found: 360.2048.

Synthesis of L7



To the solution of 2-(2-hydroxypropan-2-yl)cyclohexanone [S2] (312 mg, 2.0 mmol) in 1,1-dimethylhydrazine (3 mL), trimethylsilyl chloride (0.5 mL, 4.0 mmol) was added and stirred for overnight at room temperature. The reaction mixture was quenched with sat. NH_4Cl aq. The organic layer was extracted with $CHCl_3$. The combined organic extracts were dried over Na_2SO_4. The crude product was purified by silica gel column chromatography (hexane / AcOEt = 1 / 1) to give **L7** (367 mg, 1.8 mmol) in 93% yield.



(*E*)-2-(2-(2,2-Dimethylhydrazono)cyclohexyl)propan-2-ol **L7**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.26 (s, 3H), 1.27 (s, 3H), 1.33–1.51 (m, 3H), 1.69–1.76 (m, 1H),

1.83–1.91 (m, 2H), 2.01–2.04 (m, 1H), 2.20 (dd, J = 4.1, 11.9 Hz, 1H), 2.46 (s, 6H), 3.35 (d, J = 13.7 Hz, 1H), 5.89 (br, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.6, 25.7, 26.6, 29.1, 29.3, 29.7, 47.7, 54.0, 72.0, 173.3; IR (neat, cm^{-1}) 3400, 2934, 2857, 2817, 2773, 1631, 1449, 1402, 1376, 1359, 1315, 1198, 1172, 1138, 1021, 978, 951, 889, 678; HRMS (ESI-TOF) *m/z* calcd. $C_{11}H_{22}N_2NaO$ 221.1630 [M+Na^+]; found: 221.1629.

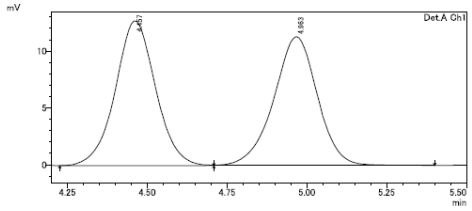
Reference

S1: Endo, K. ; Nakano, T.; Fujinami, S.; Ukaji, Y. *Eur. J. Org. Chem.* **2013**, 6514-6518.

S2: Honda, T.; Monocyclic Cyanoenones and Methods of Thereof, WO2010/011782 A1, 28 January 2010.

2a: HPLC (CHIRALPAK AD-H, Daicel, 4.6 x 250 mm, hexane/IPA = 95/5, 1.0 mL/min, 254 nm), tr (major) = 4.4 min, tr (minor) = 4.9 min.

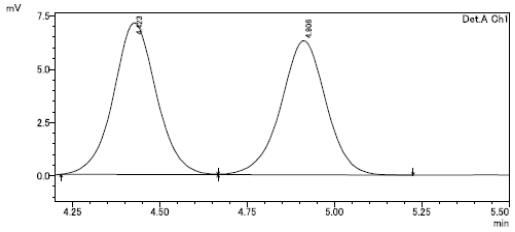
HPLC chart of *racemic* **2a**



検出器A Ch1 254nm

ピーク#	保持時間	面積	高さ	面積%	高さ%
1	4.457	112086	12721	50.894	52.877
2	4.963	108148	11337	49.106	47.123
合計		220234	24057	100.000	100.000

HPLC chart of *achiral* **2a** (4% ee) with **L9**



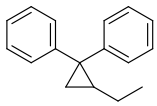
検出器A Ch1 254nm

ピーク#	保持時間	面積	高さ	面積%	高さ%
1	4.423	60893	7119	51.777	53.118
2	4.908	56714	6283	48.223	46.882
合計		117607	13402	100.000	100.000

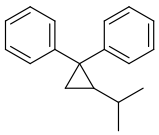
Chapter 3

General Procedure

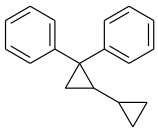
To a solution of CuI (2.9 mg, 0.015 mmol) in toluene (1.5 mL), Et_2Zn (0.6 mL, 1.0 M in toluene) was added at room temperature. After stirring for 30 min, **L1** (5.4 mg, 0.23 mmol) and cyclopropene **8b** (57.7 mg, 0.3 mmol) were added at room temperature. The reaction mixture was stirred for 16 h and was quenched with a sat. NH_4Cl. The aqueous layer was separated and extracted with AcOEt. The combined organic layer was dried over Na_2SO_4. Concentration and purification by silica gel column chromatography (hexane) gave the **11b-Et** in 86% yield.



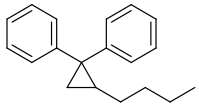
(2-Ethylcyclopropane-1,1-diyl)dibenzene **11b-Et**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67-0.80 (m, 1H), 0.89 (t, *J* = 6.9 Hz, 3H), 1.08-1.15 (m, 2H), 1.28-1.38 (m, 1H), 1.45-1.52 (m, 1H), 7.01-7.26 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.7, 20.5, 24.1, 28.4, 35.5, 125.5, 126.1, 127.7, 128.0, 128.1, 130.6, 141.9, 147.6; IR (neat, cm^{-1}) 3420, 3059, 3024, 2995, 2959, 2929, 2871, 1943, 1599, 1494, 1445, 1375, 1312, 1143, 1075, 1031, 933, 808, 748, 698; HRMS (APCI-TOF) *m/z* calcd. $C_{17}H_{18}$ 222.1409 [M^+]; found: 222.1407.



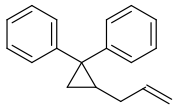
(2-Isopropylcyclopropane-1,1-diyl)dibenzene **11b-*i*-Pr** (57.3 mg, 0.24 mmol) was obtained in 81% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.64-0.73 (m, 1H), 0.88 (d, *J* = 6.4 Hz, 3H), 0.92 (d, *J* = 6.4 Hz, 3H), 1.01 (dd, *J* = 4.6, 9.2 Hz, 1H), 1.18-1.22 (m, 1H), 1.31-1.37 (m, 1H), 7.03-7.26 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 18.5, 22.2, 22.6, 28.6, 34.5, 36.5, 125.7, 126.0, 127.9, 128.1, 128.6, 130.1, 141.8, 147.6; IR (neat, cm^{-1}) 3419, 3058, 3024, 2867, 1943, 1801, 1599, 1494, 1445, 1379, 1362, 1310, 1197, 1157, 1073, 1030, 965, 943, 916, 828, 751, 699; HRMS (APCI-TOF) *m/z* calcd. $C_{18}H_{20}$ 236.1562 [M^+]; found: 236.1562.



[1,1'-Bi(cyclopropane)]-2,2-diyldibenzene **11b-*c*-Pr** (61.8 mg, 0.26 mmol) was obtained in 88% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.11-0.18 (m, 1H), 0.20-0.32 (m, 3H), 0.42-0.51 (m, 1H), 1.21-1.30 (m, 3H), 7.07-7.13 (m, 3H), 7.18-7.22 (m, 3H), 7.30 (m, 2H), 7.45 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 4.44, 4.92, 11.8, 20.1, 30.8, 35.2, 125.4, 126.2, 127.2, 128.0, 128.1, 130.1, 142.2, 147.4; IR (neat, cm^{-1}) 3058, 3022, 2998, 1944, 1802, 1654, 1599, 1494, 1445, 1312, 1154, 1076, 1018, 961, 891, 817, 762, 701; HRMS (DART) *m/z* calcd. $C_{18}H_{19}$ 235.1486 [M+H $^{+}$]; found: 235.1476.

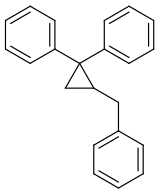


(2-Butylcyclopropane-1,1-diyl)dibenzene **11b-*n*-Bu** (63.0 mg, 0.25 mmol) was obtained in 84% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.70-0.77 (m, 1H), 0.82 (t, *J* = 6.9 Hz, 3H), 1.16-1.29 (m, 4H), 1.35-1.48 (m, 3H), 1.55-1.62 (m, 1H), 7.08-7.33 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 20.9, 22.5, 26.6, 30.6, 31.7, 35.2, 125.5, 126.1, 127.6, 128.1 (2 carbons overlapped), 130.6, 141.9, 147.7; IR (neat, cm^{-1}) 3058, 3023, 2996, 2955, 2927, 2855, 1943, 1801, 1599, 1494, 1445, 1377, 1325, 1143, 1076, 1027, 933, 824, 752, 699; HRMS (APCI-TOF) *m/z* calcd. $C_{19}H_{22}$ 250.1722 [M $^{+}$]; found: 250.1718.

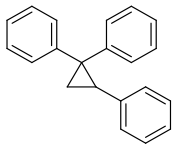


(2-Allylcyclopropane-1,1-diyl)dibenzene **11b-Allyl** (59.7 mg, 0.26 mmol) was obtained in 85% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.22-1.30 (m, 2H), 1.56-1.62 (m, 1H), 1.66-1.73 (m, 1H), 2.09-2.17 (m, 1H), 4.98 (d, *J* = 10.1 Hz, 1H), 5.04 (d, *J* = 17.4 Hz, 1H), 5.84-5.94 (m, 1H), 7.10-7.35 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5, 25.2, 35.0, 35.4, 114.7, 125.6, 126.3, 127.6, 128.2 (2 carbons overlapped), 130.6, 137.7, 141.6, 147.2; IR (neat, cm^{-1}) 3419, 3059, 3023, 2999, 2976, 2906, 1944, 1802, 1749, 1639, 1599, 1494, 1445, 1314, 1261, 1077, 1027, 997, 912, 797, 752, 698; HRMS

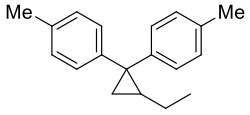
(APCI-TOF) *m/z* calcd. $C_{18}H_{18}$ 234.1409 [M $^+$]; found: 234.1403.



(2-Benzylcyclopropane-1,1-diyl)dibenzene **11b-Bn** (65.6 mg, 0.23 mmol) was obtained in 77% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.34 (dd, *J* = 5.5, 8.7 Hz, 1H), 1.40 (t, *J* = 5.5 Hz, 1H), 1.91-1.98 (m, 1H), 2.07 (dd, *J* = 9.2, 14.6 Hz, 1H), 2.79 (dd, *J* = 5.0, 14.6 Hz, 1H), 7.01-7.26 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.2, 27.1, 35.5, 36.9, 125.6, 125.8, 126.4, 127.5, 128.1, 128.2 (2 carbons overlapped), 128.3, 130.7, 141.4, 141.6, 147.1; IR (neat, cm^{-1}) 3421, 3059, 3024, 2916, 1944, 1600, 1494, 1445, 1326, 1155, 1122, 1077, 1028, 916, 844, 753, 697; HRMS (APCI-TOF) *m/z* calcd. $C_{22}H_{20}$ 284.1565 [M $^+$]; found: 284.1568.

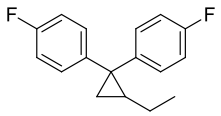


Cyclopropane-1,1,2-triyltribenzene **11b-Ph** (75.4 mg, 0.28 mmol) was obtained in 93% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.80 (dd, *J* = 5.5, 9.2 Hz, 1H), 1.97 (dd, *J* = 5.5, 6.4 Hz, 1H), 2.84 (dd, *J* = 6.4, 9.2 Hz, 1H), 6.85 (m, 2H), 7.01-7.18 (m, 9H), 7.24-7.30 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.9, 32.4, 39.3, 125.6, 125.9, 126.2, 127.4, 127.6, 127.9 (2 carbons overlapped), 128.3, 131.2, 138.7, 140.1, 147.0; IR (neat, cm^{-1}) 3055, 3027, 2998, 1597, 1496, 1457, 1445, 1314, 1210, 1186, 1157, 1132, 1094, 1074, 1032, 962, 931, 849, 825, 776, 758, 733, 696; HRMS (APCI-TOF) *m/z* calcd. $C_{21}H_{18}$ 270.1409 [M $^+$]; found: 270.1406.

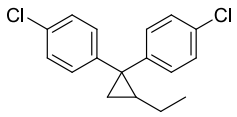


4,4'-(2-Ethylcyclopropane-1,1-diyl)bis(methylbenzene) **11c** (54.8 mg, 0.22 mmol) was obtained in 73% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.69-0.79 (m, 1H), 0.89 (t, *J* = 7.3 Hz, 3H), 1.02-1.09 (m, 2H), 1.27-1.37 (m, 1H), 1.40-1.47 (m, 1H), 6.94

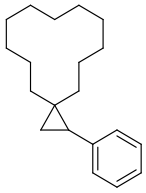
(m, 2H), 6.98-7.04 (m, 4H), 7.12 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.8, 20.4, 20.9, 21.1, 24.1, 28.1, 34.7, 127.5, 128.8 (2 carbons overlapped), 130.3, 134.9, 135.5, 139.1, 144.9; IR (neat, cm^{-1}) 3419, 2994, 2958, 2921, 2870, 1650, 1513, 1455, 1112, 1076, 1037, 821, 772, 726; HRMS (APCI-TOF) *m/z* calcd. $C_{19}H_{22}$ 250.1722 [M^+]; found: 250.1720.



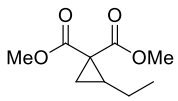
4,4'-(2-Ethylcyclopropane-1,1-diyl)bis(fluorobenzene) **11d** (63.5 mg, 0.25 mmol) was obtained in 82% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.72-0.86 (m, 1H), 0.97 (t, J = 7.3 Hz, 3H), 1.10-1.17 (m, 2H), 1.32-1.42 (m, 1H), 1.47-1.55 (m, 1H), 6.87-7.00 (m, 4H), 7.10-7.15 (m, 2H), 7.23-7.27 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.7, 20.5, 24.0, 28.2, 34.3, 114.9 (d, J = 21.0 Hz), 115.0 (d, J = 21.0 Hz), 129.2 (d, J = 7.6 Hz), 131.7 (d, J = 7.6 Hz), 137.6, 143.1, 161.0 (d, J = 243 Hz), 161.4 (d, J = 243 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –120.31, –119.39; IR (neat, cm^{-1}) 3384, 3067, 2961, 2931, 2873, 1888, 1602, 1509, 1456, 1405, 1375, 1296, 1221, 1157, 1095, 1076, 1033, 1015, 835, 782, 769, 730; HRMS (APCI-TOF) *m/z* calcd. $C_{17}H_{16}F_2$ 258.1220 [M^+]; found: 258.1224.



4,4'-(2-Ethylcyclopropane-1,1-diyl)bis(chlorobenzene) **11e** (85.2 mg, 0.29 mmol) was obtained in 98% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67-0.78 (m, 1H), 0.89 (t, J = 6.8 Hz, 3H), 1.05-1.11 (m, 2H), 1.24-1.34 (m, 1H), 1.42-1.49 (m, 1H), 6.98-7.01 (m, 2H), 7.09-7.19 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.6, 20.7, 24.0, 28.4, 34.4, 128.3, 128.4, 129.0, 131.5, 131.7, 132.2, 140.0, 145.5; IR (neat, cm^{-1}) 3418, 2960, 2929, 2871, 1723, 1593, 1492, 1455, 1398, 1092, 1014, 831, 808, 727; HRMS (APCI-TOF) *m/z* calcd. $C_{17}H_{16}Cl_2$ 290.0629 [M^+]; found: 290.0627.



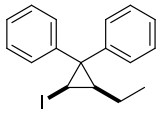
1-Phenylspiro[2.11]tetradecane **11f** (73.7 mg, 0.27 mmol) was obtained in 91% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.48-0.60 (m, 2H), 0.66 (t, J = 6.4 Hz, 1H), 0.78-0.92 (m, 2H), 0.99-1.16 (m, 5H), 1.21-1.37 (m, 4H), 1.39-1.59 (m, 5H), 1.66-1.86 (m, 5H), 2.07 (t, J = 7.3 Hz, 1H), 7.10-7.26 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.0, 26.5 (2 carbons overlapped), 26.8, 27.1, 27.2, 27.3, 29.7, 30.6, 32.1, 33.6, 36.3, 37.6, 43.5, 125.2, 127.5, 129.0, 139.9; IR (neat, cm^{-1}) 3384, 3060, 3024, 2923, 2850, 1602, 1497, 1448, 1073, 1041, 867, 774, 729, 698; HRMS (APCI-TOF) *m/z* calcd. $C_{20}H_{30}$ 270.2348 [M^+]; found: 270.2343.



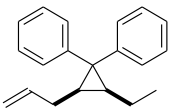
Dimethyl 2-ethylcyclopropane-1,1-dicarboxylate **11g** (38.1 mg, 0.20 mmol) was obtained in 68% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.94 (t, J = 7.4 Hz, 3H), 1.13-1.23 (m, 1H), 1.29-1.42 (m, 3H), 1.77-1.85 (m, 1H), 3.65 (s, 3H), 3.69 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.1, 21.1, 22.1, 30.4, 34.0, 52.4, 52.5, 168.7, 170.9; IR (neat, cm^{-1}) 3448, 2957, 2878, 1727, 1437, 1389, 1326, 1289, 1262, 1213, 1132, 1104, 1041, 990, 882, 808; HRMS (DART) *m/z* calcd. $C_9H_{15}O_4$ 187.0970 [M+H^+]; found: 187.0970.

General Procedure for Electrophilic Trapping Reaction

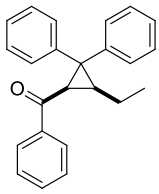
To a solution of CuI (2.9 mg, 0.015 mmol) in toluene (1.5 mL), Et_2Zn (0.6 mL, 1.0 M in toluene) was added at room temperature. After stirring for 30 min, **L1** (5.4 mg, 0.23 mmol) and cyclopropene **8b** (57.7 mg, 0.3 mmol) were added at room temperature. After stirred for 6 h, CuI (116 mg, 0.6 mmol) and the solution of I_2 (228 mg, 0.9 mmol) in CH_2Cl_2 (1.5 mL) were added. The reaction mixture was stirred for 15 h at 60 °C and was quenched with a sat. NH_4Cl. The aqueous layer was separated and extracted with AcOEt and dried over Na_2SO_4. Concentration and purification by silica gel column chromatography (hexane) gave the **12b-Et-I** in 86% yield.



(2-Ethyl-3-iodocyclopropane-1,1-diyl)dibenzene **12b-Et-I**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.92-1.05 (m, 4H), 1.32-1.37 (m, 1H), 1.78-1.85 (m, 1H), 3.44 (d, J = 8.2 Hz, 1H), 7.03-7.09 (m, 3H), 7.12-7.20 (m, 3H), 7.27 (m, 2H), 7.35 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 10.3, 12.5, 26.4, 31.1, 37.1, 126.2, 126.9, 127.0, 128.2, 128.5, 131.5, 139.3, 146.3; IR (neat, cm^{-1}) 3025, 2962, 2927, 2870, 1597, 1493, 1445, 1375, 1247, 1201, 1078, 1030, 745, 703; HRMS (ESI-TOF) *m/z* calcd. $C_{17}H_{17}INa$ 371.0273 [M+Na $^{+}$]; found: 371.0278.

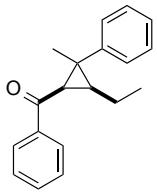


(2-Allyl-3-ethylcyclopropane-1,1-diyl)dibenzene **12b-Et-Allyl** (49.5 mg, 0.19 mmol) was obtained in 63% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.04 (t, J = 6.9 Hz, 3H), 1.07-1.16 (m, 1H), 1.39-1.44 (m, 1H), 1.51-1.61 (m, 2H), 1.87-1.94 (m, 1H), 2.19-2.26 (m, 1H), 5.01 (d, J = 10.5 Hz, 1H), 5.09 (d, J = 17.4 Hz, 1H), 5.91-6.01 (m, 1H), 6.98-7.28 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.7, 19.9, 28.7, 30.5, 31.8, 37.1, 114.9, 125.3, 126.3, 127.0, 128.1, 128.3, 131.7, 138.4, 139.5, 149.1; IR (neat, cm^{-1}) 3057, 2961, 2872, 1638, 1599, 1494, 1445, 1376, 1077, 1031, 992, 911, 746, 705; HRMS (APCI-TOF) *m/z* calcd. $C_{20}H_{22}$ 262.1721 [M $^{+}$]; found: 262.1698.

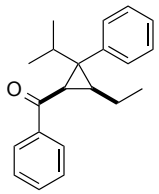


(3-Ethyl-2,2-diphenylcyclopropyl)(phenyl)methanone **12b-Et-Bz** (84.1 mg, 0.26 mmol) was obtained in 86% yield; white solid of mp = 96−97 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.99 (t, J = 7.3 Hz, 3H), 1.85-1.96 (m, 1H), 1.98-2.09 (m, 1H), 2.27-2.33 (m, 1H), 3.40 (d, J = 8.7 Hz, 1H), 7.14-7.33 (m, 10H), 7.47-7.51 (m, 2H), 7.55-7.59 (m, 1H), 7.99-8.02 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.2, 18.6, 34.4, 39.5, 47.6, 126.4, 126.6, 127.4, 127.7, 128.2, 128.5, 128.6, 130.9, 132.3, 137.4, 140.2, 147.2, 196.9; IR (neat, cm^{-1}) 3057, 2958, 2928, 2873, 1734, 1670, 1578, 1493, 1446, 1409, 1381, 1214,

1178, 1078, 1020, 848, 741, 718, 702, 672; HRMS (EI) *m/z* calcd. $C_{24}H_{22}O$ 326.1671 [M^+]; found: 326.1669.



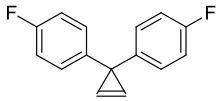
3-Ethyl-2-methyl-2-phenylcyclopropyl)(phenyl)methanone **12a** (47.4 mg, 0.18 mmol) was obtained in 60% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 0.97 (t, *J* = 6.9 Hz, 3H), 1.51 (s, 3H), 1.78-1.97 (m, 3H), 2.84 (d, *J* = 8.2 Hz, 1H), 7.10-7.20 (m, 2H), 7.23-7.27 (m, 3H), 7.35-7.41 (m, 2H), 7.43-7.47 (m, 1H), 7.86-7.89 (m, 2H); (minor) δ 0.79 (t, *J* = 6.9 Hz, 3H), 1.45 (s, 3H), 1.78-1.97 (m, 3H), 2.82 (d, *J* = 7.3 Hz, 1H), 6.96-6.98 (m, 2H), 7.23-7.27 (m, 3H), 7.35-7.41 (m, 2H), 7.43-7.47 (m, 1H), 7.86-7.89 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) (major) δ 14.1, 15.3, 16.7, 33.2, 37.7 (2 carbons overlapped), 126.4, 127.4, 127.7, 128.4, 128.6, 132.3, 140.0, 148.2, 198.8; (minor) δ 14.3, 18.4, 32.3, 33.8, 39.8, 41.0, 126.3, 127.6, 128.1, 130.0, 132.0, 139.5, 140.4, 146.8, 197.2; IR (neat, cm^{-1}) 3058, 2959, 1665, 1597, 1579, 1494, 1447, 1414, 1379, 1214, 1179, 1065, 1023, 969, 892, 855, 764, 719, 700; HRMS (ESI-TOF) *m/z* calcd. $C_{19}H_{20}ONa$ 287.1412 [$M+Na^+$]; found: 287.1420.



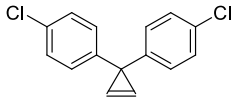
3-Ethyl-2-isopropyl-2-phenylcyclopropyl)(phenyl)methanone **12h** (31.5 mg, 0.11 mmol) was obtained in 36% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 0.79-0.86 (m, 9H), 1.20-1.30 (m, 1H), 1.58-1.68 (m, 2H), 1.70-1.84 (m, 1H), 2.80 (d, *J* = 7.8 Hz, 1H), 6.85-6.87 (m, 1H), 7.13-7.21 (m, 3H), 7.22-7.26 (m, 1H), 7.38-7.42 (m, 2H), 7.44-7.49 (m, 1H), 7.90-7.94 (m, 2H); (minor) δ 0.66 (d, *J* = 7.8 Hz, 3H), 0.78 (d, *J* = 6.9 Hz, 3H), 0.94 (t, *J* = 7.3 Hz, 3H), 1.15-1.30 (m, 1H), 1.91-2.09 (m, 2H), 2.73-2.78 (m, 1H), 2.91 (d, *J* = 8.7 Hz, 1H), 6.85-6.87 (m, 3H), 7.13-7.21 (m, 1H), 7.22-7.26 (m, 1H), 7.38-7.42 (m, 2H), 7.44-7.49 (m, 1H), 7.90-7.94 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) (major) δ 14.3, 18.4, 19.5, 19.8, 33.8, 40.9, 41.8, 49.7, 126.4, 127.0,

127.6, 128.4, 131.1, 132.0, 132.5, 140.5, 197.0; (minor) δ 14.5, 16.1, 20.0, 20.7, 23.7, 32.4, 40.2, 49.5, 126.6, 127.6, 128.5, 130.6, 132.2, 133.1, 140.3, 143.4, 199.2; IR (neat, cm^{-1}) 3057, 2960, 2871, 1735, 1596, 1578, 1495, 1446, 1418, 1382, 1213, 1177, 1021, 913, 865, 804, 755, 705; HRMS (ESI-TOF) *m/z* calcd. $C_{21}H_{24}ONa$ 315.1725 [M+Na^+]; found: 315.1726.

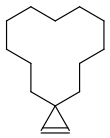
Cyclopropene substrates were synthesized from ketones for 4 steps. [S1]



4,4'-(Cycloprop-2-ene-1,1-diyl)bis(fluorobenzene) **8d** (1.33 g, 5.8 mmol) was obtained in 39% yield (4 steps); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.93-6.98 (m, 4H), 7.08-7.11 (m, 4H), 7.46 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 30.6, 113.4, 114.8 (d, *J* = 21.0 Hz), 129.4 (d, *J* = 7.6 Hz), 142.6, 161.1 (d, *J* = 243 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –120.10; IR (neat, cm^{-1}) 3383, 1893, 1642, 1600, 1507, 1405, 1219, 1156, 1094, 1014, 995, 906, 863, 836, 814, 725; HRMS (APCI-TOF) *m/z* calcd. $C_{15}H_{10}F_2$ 228.0751 [M^+]; found: 228.0748.



4,4'-(Cycloprop-2-ene-1,1-diyl)bis(chlorobenzene) **8e** (1.20 g, 4.6 mmol) was obtained in 31% yield (4 steps); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.05-7.08 (m, 4H), 7.21-7.25 (m, 4H), 7.45 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 30.9, 113.0, 128.2, 129.3, 131.6, 145.0; IR (neat, cm^{-1}) 3105, 1906, 1647, 1559, 1482, 1398, 1272, 1089, 1008, 946, 903, 859, 832, 795, 742, 722; HRMS (APCI-TOF) *m/z* calcd. $C_{15}H_{10}Cl_2$ 260.0160 [M^+]; found: 260.0159.



Spiro[2.11]tetradec-1-ene **8f** (555 mg, 2.9 mmol) was obtained in 19% yield (4 steps); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.51-0.62 (m, 4H), 0.91-1.03 (m, 2H), 1.15-1.28 (m, 4H), 1.41-1.48 (m, 6H), 1.56-1.60 (m, 2H), 1.64-1.69 (m, 4H), 7.10 (s,

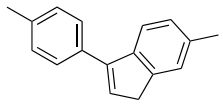
2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 26.5, 26.6 (2 carbons overlapped), 30.9 (2 carbons overlapped), 34.9, 41.5, 113.9; IR (neat, cm^{-1}) 3420, 2920, 2849, 2667, 1630, 1447, 1382, 1306, 1008, 988, 933, 896, 851, 784, 698; HRMS (DART) *m/z* calcd. $C_{14}H_{25}$ 193.1956 [M+H $^+$]; found: 193.1961.

(S1) Krämer, K.; Leong, P.; Lautens. M. *Org. Lett.* **2011**, *13*, 819–821.

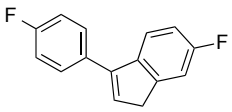
Chapter 4

General Procedure (Preparation of Indene)

To a suspension of AgOTf (3.9 mg, 0.0015 mmol) in CH_2Cl_2 (1.5 mL), cyclopropene **8c** (66.0 mg, 0.3 mmol) was added at room temperature. The reaction mixture was stirred for 18 h and was quenched with a sat. NH_4Cl. The aqueous layer was separated and extracted with $CHCl_3$. The combined organic layer was dried over Na_2SO_4. Concentration and purification by silica gel column chromatography (haxane) gave **13c** (60.7 mg, 0.27 mmol) in 92% yield.

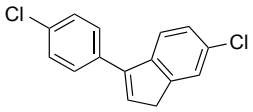


6-Methyl-3-(*p*-tolyl)-1*H*-indene **13c**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.32 (s, 3H), 2.34 (s, 3H), 3.37 (d, *J* = 1.8 Hz, 2H), 6.39 (t, *J* = 1.8 Hz, 1H), 7.04–7.06 (m, 1H), 7.15–7.18 (m, 2H), 7.26 (s, 1H), 7.38–7.43 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.2, 21.4, 37.9, 120.0, 125.0, 126.8, 127.5, 129.2, 129.4, 133.4, 134.4, 137.2, 141.4, 144.8, 145.1; IR (neat, cm^{-1}) 3440, 3022, 2918, 1655, 1609, 1570, 1508, 1475, 1449, 1390, 1341, 1250, 1183, 1109, 1037, 970, 941, 867, 825, 770; HRMS (APCI) *m/z* calcd. $C_{17}H_{16}$ 220.1252 [M^+]; found: 220.1250.

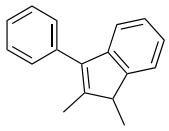


6-Fluoro-3-(4-fluorophenyl)-1*H*-indene **13d** (66.3 mg, 0.29 mmol) was obtained in 97% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.39 (d, *J* = 1.8 Hz, 2H), 6.41 (t, *J* =

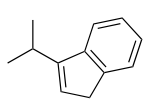
1.8 Hz, 1H), 6.91–6.96 (m, 1H), 7.02–7.08 (m, 2H), 7.13–7.16 (m, 1H), 7.32–7.36 (m, 1H), 7.42–7.47 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ ; 38.1, 111.7 (d, *J* = 22.9 Hz), 113.1 (d, *J* = 22.9 Hz), 115.5 (d, *J* = 21.0 Hz), 120.6 (d, *J* = 9.5 Hz), 129.2 (d, *J* = 7.6 Hz), 130.3, 131.9, 139.7, 143.5, 146.7 (d, *J* = 8.8 Hz), 161.5 (d, *J* = 242 Hz), 162.4 (d, *J* = 245 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –118.34, –114.19; IR (neat, cm^{-1}) 3066, 2887, 1613, 1581, 1506, 1475, 1409, 1390, 1343, 1282, 1236, 1157, 1141, 1124, 1095, 950, 924, 841, 812, 776, 761; HRMS (APCI) *m/z* calcd. $C_{15}H_{10}F_2$ 228.0751 [M^+]; found: 228.0748.



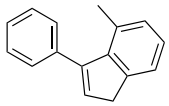
6-Chloro-3-(4-chlorophenyl)-1*H*-indene **13e** (74.8 mg, 0.28 mmol) was obtained in 96% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.40 (d, *J* = 2.3 Hz, 2H), 6.48 (t, *J* = 2.3 Hz, 1H), 7.20–7.22 (m, 1H), 7.32–7.35 (m, 3H), 7.39–7.42 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 38.0, 120.8, 124.5, 126.4, 128.8 (2 carbons overlapped), 131.2, 131.5, 133.6, 134.0, 142.0, 143.5, 146.3; IR (neat, cm^{-1}) 3065, 2884, 1654, 1600, 1564, 1488, 1459, 1418, 1388, 1338, 1272, 1187, 1143, 1090, 1068, 1014, 973, 939, 872, 835, 776, 752, 685; HRMS (APCI) *m/z* calcd. $C_{15}H_{10}Cl_2$ 260.0160 [M^+]; found: 260.1059.



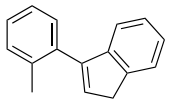
1,2-Dimethyl-3-phenyl-1*H*-indene **13i** (62.6 mg, 0.28 mmol) was obtained in 95% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31 (d, *J* = 7.8 Hz, 3H), 1.98 (s, 3H), 3.29 (q, *J* = 7.8 Hz, 1H), 7.07–7.16 (m, 3H), 7.25–7.29 (m, 1H), 7.32–7.40 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 15.8, 47.4, 119.2, 122.5, 124.1, 126.3, 126.9, 128.3, 129.2, 135.5, 137.1, 144.9, 145.6, 148.2; IR (neat, cm^{-1}) 3018, 2964, 2927, 2868, 1597, 1493, 1463, 1442, 1352, 1158, 1074, 1023, 934, 772, 701, 658; HRMS (APCI) *m/z* calcd. $C_{17}H_{16}$ 220.1252 [M^+]; found: 220.1250.



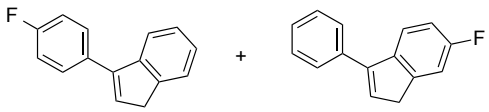
3-Isopropyl-1*H*-indene **13h** (29.8 mg, 0.18 mmol) was obtained in 63% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.21 (d, *J* = 6.9 Hz, 6H), 2.83–2.90 (m, 1H), 3.24 (s, 2H), 6.12 (s, 1H), 7.10–7.13 (m, 1H), 7.20–7.24 (m, 1H), 7.32–7.34 (m, 1H), 7.37–7.39 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.9, 26.9, 37.5, 119.3, 123.8, 124.3, 125.3, 125.8, 144.8, 145.0, 151.0; IR (neat, cm^{-1}) 3067, 3017, 2961, 2871, 1718, 1605, 1457, 1395, 1381, 1360, 1271, 1158, 1110, 1015, 968, 915, 766, 720; HRMS (ESI-TOF) *m/z* calcd. $C_{13}H_{15}$ 159.1174 [M+H$^+$]; found: 159.1173.



4-Methyl-3-phenyl-1*H*-indene **13j** (45.6 mg, 0.22 mmol) was obtained in 74% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.93 (s, 3H), 3.38 (d, *J* = 1.8 Hz, 2H), 6.28 (t, *J* = 1.8 Hz, 1H), 6.93–6.95 (m, 1H), 7.04–7.08 (m, 1H), 7.13–7.32 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.3, 38.0, 121.7, 124.9, 127.0, 127.8, 128.9, 129.0, 131.5, 132.6, 139.2, 142.4, 144.8, 146.9; IR (neat, cm^{-1}) 3422, 3058, 2923, 1654, 1594, 1542, 1509, 1490, 1457, 1389, 765, 701; HRMS (APCI) *m/z* calcd. $C_{16}H_{14}$ 206.1096 [M$^+$]; found: 206.1093.

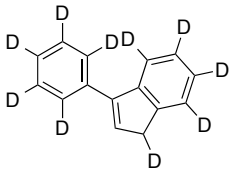


3-(*o*-Tolyl)-1*H*-indene **13j'** (14.2 mg, 0.06 mmol) was obtained in 23% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.18 (s, 3H), 3.46 (d, *J* = 1.8 Hz, 2H), 6.35 (t, *J* = 1.8 Hz, 1H), 7.04–7.08 (m, 1H), 7.13–7.32 (m, 6H), 7.45–7.47 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.2, 38.4, 120.5, 123.8, 124.7, 125.6, 126.1, 127.5, 129.4, 130.2, 131.6, 135.7, 136.4, 143.9, 145.0, 145.2; IR (neat, cm^{-1}) 3422, 3058, 2923, 1654, 1594, 1542, 1509, 1490, 1457, 1389, 765, 701; HRMS (APCI) *m/z* calcd. $C_{16}H_{14}$ 206.1096 [M$^+$]; found: 206.1093.



3-(4-Fluorophenyl)-1*H*-indene **13k** (30.2 mg, 0.14 mmol) was obtained in 48% yield; colorless oil; 6-fluoro-3-phenyl-1*H*-indene **13k'** (30.2 mg, 0.14 mmol) was obtained in

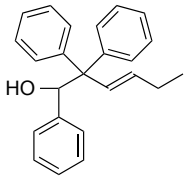
48% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.40–3.43 (m, 2H), 6.45–6.47 (m, 1H), 6.85–7.51 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ ; 38.1, 111.7 (d, *J* = 22.9 Hz), 113.1 (d, *J* = 22.9 Hz), 115.5 (d, *J* = 21.0 Hz), 120.1, 120.8 (d, *J* = 8.6 Hz), 124.1, 124.9, 126.2, 127.6, 127.7, 128.6, 129.3 (d, *J* = 7.6 Hz), 130.3, 130.9, 132.1, 135.8, 139.9, 143.8, 144.2, 144.5, 144.7, 146.8 (d, *J* = 8.6 Hz), 161.5 (d, *J* = 241 Hz), 162.3 (d, *J* = 246 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –118.56, –114.50; IR (neat, cm^{-1}) 3064, 2884, 2768, 1890, 1655, 1613, 1596, 1505, 1475, 1445, 1390, 1348, 1294, 1274, 1234, 1157, 1141, 1123, 1095, 1081, 1024, 972, 948, 922, 841, 814, 765, 720; HRMS (APCI) *m/z* calcd. $C_{15}H_{11}F$ 210.0845 [M^+]; found: 210.0843.



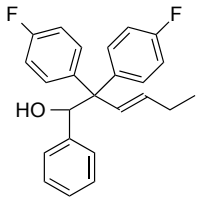
3-Phenyl-1*H*-indene 1,1'-(cycloprop-2-ene-1,1-diyl)bis(benzene-2,3,4,5,6-d_5) ***d*-13b** (49.0 mg, 0.24 mmol) was obtained in 81% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.43 (d, *J* = 2.3 Hz, 1H), 6.50 (d, *J* = 2.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 37.8 (t, *J* = 19.1 Hz), 119.9 (t, *J* = 24.8 Hz), 123.7 (t, *J* = 24.8 Hz), 124.3 (t, *J* = 23.8 Hz), 125.6 (t, *J* = 23.8 Hz), 127.0 (t, *J* = 23.8 Hz), 127.4 (t, *J* = 23.8 Hz), 128.0 (t, *J* = 23.8 Hz), 130.9, 136.0, 143.9, 144.6, 145.2; IR (neat, cm^{-1}) 2923, 2275, 1654, 1560, 1375, 1327, 1247, 1017, 927, 853, 821, 769, 731; HRMS (ESI-TOF) *m/z* calcd. $C_{15}H_3D_{10}$ 203.1645 [M+H^+]; found: 203.1643.

General Procedure (Preparation of 17aa)

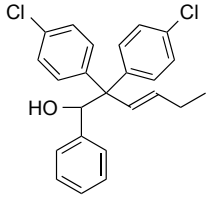
To a suspension of AgOAc (2.5 mg, 0.0015 mmol) in CH_2Cl_2 (1.5 mL), cyclopropene **8b** (57.6 mg, 0.3 mmol), Et_2Zn (0.9 mL, 1.0 M in toluene), and benzaldehyde (31.8 mL) were added at room temperature. The reaction mixture was stirred for 18 h and was quenched with a sat. NH_4Cl. The aqueous layer was separated and extracted with $CHCl_3$. The combined organic layer was dried over Na_2SO_4. Concentration and purification by silica gel column chromatography (hexane/AcOEt = 20/1) gave **9ba** (55.0 mg, 0.16 mmol) in 56% yield.



(*E*)-1,2,2-Triphenylhex-3-en-1-ol **9ba**; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.93 (t, *J* = 7.3 Hz, 3H), 2.02–2.09 (m, 2H), 2.40 (br, 1H), 5.08 (dt, *J* = 16.0, 6.0 Hz, 1H), 5.47 (s, 1H), 5.99 (d, *J* = 16.0 Hz, 1H), 6.70–6.72 (m, 2H), 6.99–7.32 (m, 13H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.6, 26.0, 59.6, 77.9, 126.2, 126.3, 127.0, 127.2, 127.4, 127.7, 128.3, 129.2, 130.6, 131.1, 137.6, 140.7, 143.8, 145.1; IR (neat, cm^{-1}) 3547, 3057, 3030, 2961, 2929, 1719, 1654, 1599, 1494, 1444, 1379, 1333, 1186, 1083, 1042, 910, 732, 700 ; HRMS (ESI-TOF) *m/z* calcd. $C_{24}H_{24}NaO$ 351.1725 [M+Na^+]; found: 351.1731.

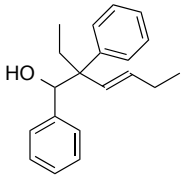


(*E*)-2,2-Bis(4-fluorophenyl)-1-phenylhex-3-en-1-ol **9da** (36.0 mg, 0.09 mmol) was obtained in 33% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.92 (t, *J* = 7.3 Hz, 3H), 1.97–2.10 (m, 2H), 2.28 (d, *J* = 6.0 Hz, 1H), 5.03 (dt, *J* = 15.6, 6.4 Hz, 1H), 5.37 (t, *J* = 6.0 Hz, 1H), 5.91 (d, *J* = 15.6 Hz, 1H), 6.69–6.71 (m, 2H), 6.80–6.98 (m, 6H), 7.03–7.13 (m, 3H), 7.21–7.26 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ ; 13.6, 26.0, 58.5, 78.2, 114.2 (d, *J* = 21.0 Hz), 114.5 (d, *J* = 21.0 Hz), 127.2, 127.5, 128.2, 130.8 (d, *J* = 7.6 Hz), 131.2, 132.1 (d, *J* = 7.6 Hz), 137.7, 139.3, 140.4, 140.8, 161.2 (d, *J* = 244 Hz), 161.5 (d, *J* = 244 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –116.44, –116.31; IR (neat, cm^{-1}) 3448, 3032, 2962, 2927, 1603, 1508, 1455, 1232, 1162, 1108, 1044, 911, 835, 764, 734, 703; HRMS (ESI-TOF) *m/z* calcd. $C_{24}H_{22}F_2NaO$ 387.1536 [M+Na^+]; found: 387.1535.

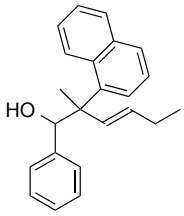


(*E*)-2,2-Bis(4-chlorophenyl)-1-phenylhex-3-en-1-ol **9ea** (56.8 mg, 0.14 mmol) was

obtained in 48% yield; white solid of mp = 112–113 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.91 (t, *J* = 7.8 Hz, 3H), 2.00–2.07 (m, 2H), 2.26 (br, 1H), 5.03 (dt, *J* = 15.6, 6.4 Hz, 1H), 5.36 (s, 1H), 5.87 (d, *J* = 15.6 Hz, 1H), 6.70–6.72 (m, 2H), 6.91–6.94 (m, 2H), 7.04–7.21 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.5, 26.0, 58.7, 78.0, 127.3, 127.5, 127.6, 127.9, 128.2, 130.7, 130.8, 131.9, 132.1, 132.4, 137.9, 140.2, 141.9, 143.4; IR (neat, cm^{-1}) 3448, 2961, 1718, 1658, 1654, 1560, 1542, 1508, 1490, 1457, 1398, 1260, 1093, 1012, 801, 701; HRMS (ESI-TOF) *m/z* calcd. $C_{24}H_{22}Cl_2NaO$ 419.0945 [M+Na^+]; found: 419.0941.

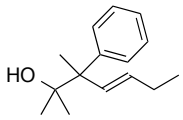


(*E*)-2-Ethyl-1,2-diphenylhex-3-en-1-ol **9la** (54.8 mg, 0.18 mmol) was obtained in 63% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 0.51 (t, *J* = 7.8 Hz, 3H), 0.95 (t, *J* = 7.8 Hz, 3H), 1.50–1.66 (m, 2H), 1.91 (d, *J* = 3.2 Hz, 1H), 2.05–2.18 (m, 2H), 5.05 (d, *J* = 3.2 Hz, 1H), 5.25 (dt, *J* = 15.6, 6.4 Hz, 1H), 5.80 (d, *J* = 15.6 Hz, 1H), 7.01–7.34 (m, 10H); (minor) δ 0.66 (t, *J* = 7.3 Hz, 3H), 1.00 (t, *J* = 7.4 Hz, 3H), 1.73–1.90 (m, 2H), 2.05–2.18 (m, 3H), 4.85 (d, *J* = 5.5 Hz, 1H), 5.57 (d, *J* = 16.0 Hz, 1H), 5.67 (dt, *J* = 16.0, 6.0 Hz, 1H), 6.69–6.71 (m, 2H), 7.01–7.34 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 8.80, 13.7, 14.0, 26.3, 27.9, 28.0, 53.7, 53.9, 80.1, 80.3, 126.2, 127.0, 127.1, 127.4, 127.5, 128.0, 128.2, 128.4, 128.5, 129.3, 131.0, 134.1, 134.3, 140.5, 140.6, 141.1, 143.1; IR (neat, cm^{-1}) 3453, 3086, 3058, 3029, 2964, 2932, 2857, 1946, 1810, 1654, 1600, 1493, 1453, 1378, 1322, 1188, 1083, 1042, 988, 914, 756, 701, 670; HRMS (ESI-TOF) *m/z* calcd. $C_{20}H_{24}NaO$ 303.1723 [M+Na^+]; found: 303.1723.

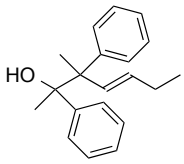


(*E*)-2-Methyl-2-(naphthalen-1-yl)-1-phenylhex-3-en-1-ol **9ma** (30.1 mg, 0.09 mmol) was obtained in 32% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 0.87 (t,

J = 7.3 Hz, 3H), 1.38 (s, 3H), 1.97–2.05 (m, 2H), 2.26 (d, *J* = 4.6 Hz, 1H), 5.16 (dt, *J* = 15.6, 6.9 Hz, 1H), 5.61 (d, *J* = 4.6 Hz, 1H), 5.87 (d, *J* = 15.6 Hz, 1H), 6.78–6.79 (m, 2H), 7.01–7.10 (m, 2H), 7.23–7.44 (m, 5H), 7.66–7.68 (m, 1H), 7.78–7.82 (m, 1H), 8.33–8.35 (m, 1H); ^{1}H NMR (400 MHz, $CDCl_3$) (minor) δ 0.72 (t, *J* = 7.3 Hz, 3H), 1.46 (s, 3H), 1.78–1.86 (m, 2H), 4.96 (dt, *J* = 16.0, 6.4 Hz, 1H), 5.54 (d, *J* = 2.3 Hz, 1H), 5.77 (d, *J* = 16.0 Hz, 1H), 6.78–6.79 (m, 2H), 7.01–7.10 (m, 2H), 7.23–7.44 (m, 5H), 7.61–7.62 (m, 1H), 7.74–7.76 (m, 1H), 8.41–8.43 (m, 1H), OH proton was not observed clearly; ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.5, 13.6, 23.1, 23.9, 25.9, 26.0, 50.4, 51.1, 77.2, 77.8, 124.2, 124.3, 124.6, 124.9, 125.0, 126.0, 127.0, 127.1, 127.3, 127.4, 127.5, 127.6, 128.1, 128.5, 128.6, 129.3, 129.4, 130.9, 131.5, 132.9, 134.0, 134.3, 134.4, 135.0, 135.3, 140.5, 140.6, 141.3; IR (neat, cm^{-1}) 3448, 3029, 2961, 2929, 1654, 1600, 1508, 1492, 1452, 1396, 1374, 1336, 1186, 1023, 975, 939, 909, 799, 778, 758, 734, 704; HRMS (ESI-TOF) *m/z* calcd. $C_{23}H_{24}NaO$ 339.1725 [M+Na^+]; found: 339.1728.

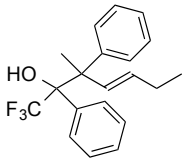


(*E*)-2,3-Dimethyl-3-phenylhept-4-en-2-ol **9aq** (44.0 mg, 0.20 mmol) was obtained in 67% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.94 (t, *J* = 7.3 Hz, 3H), 1.04 (s, 3H), 1.09 (s, 3H), 1.30 (br, 1H), 1.45 (s, 3H), 2.02–2.10 (m, 2H), 5.49 (dt, *J* = 15.6, 6.4 Hz, 1H), 6.24 (d, *J* = 15.6 Hz, 1H), 7.11–7.15 (m, 1H), 7.19–7.25 (m, 2H), 7.38–7.41 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.0, 20.9, 25.9, 26.1, 26.3, 50.3, 74.7, 126.0, 127.6, 128.5, 131.8, 134.1, 145.7; IR (neat, cm^{-1}) 3473, 2966, 2931, 1734, 1654, 1598, 1541, 1495, 1458, 1371, 1327, 1113, 1028, 985, 952, 871, 755, 702; HRMS (ESI-TOF) *m/z* calcd. $C_{15}H_{22}NaO$ 241.1568 [M+Na^+]; found: 241.1564.

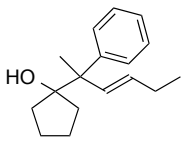


(*E*)-3-Methyl-2,3-diphenylhept-4-en-2-ol **9ar** (69.5 mg, 0.24 mmol) was obtained in 83% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 0.90 (t, *J* = 7.4 Hz, 3H), 1.37 (s, 3H), 1.45 (s, 3H), 1.89 (s, 1H), 1.97–2.08 (m, 2H), 5.40 (dt, *J* = 15.6, 6.4 Hz,

1H), 6.30 (d, *J* = 15.6 Hz, 1H), 7.00–7.20 (m, 10H); (minor) δ 0.92 (t, *J* = 7.8 Hz, 3H), 1.35 (s, 3H), 1.49 (s, 3H), 1.86 (s, 1H), 1.97–2.08 (m, 2H), 5.40 (dt, *J* = 15.6, 6.4 Hz, 1H), 6.30 (d, *J* = 15.6 Hz, 1H), 7.00–7.20 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.8, 20.9, 21.1, 25.8, 26.1, 26.2, 26.3, 50.8, 78.2, 78.4, 126.2, 126.4, 126.5, 126.6, 126.7, 127.1, 127.2, 127.26, 127.30, 128.8, 132.1, 132.2, 133.3, 133.5, 144.5, 144.7, 144.8, 144.9; IR (neat, cm^{-1}) 3567, 3089, 3056, 2961, 1654, 1599, 1493, 1444, 1372, 1330, 1170, 1069, 1027, 986, 906, 759, 701; HRMS (ESI-TOF) *m/z* calcd. $C_{20}H_{24}NaO$ 303.1725 [M+Na^+]; found: 303.1727.

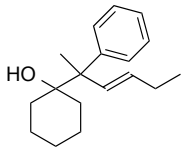


(*E*)-1,1,1-Trifluoro-3-methyl-2,3-diphenylhept-4-en-2-ol **9ap** (54.9 mg, 0.15 mmol) was obtained in 51% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) (major) δ 0.94 (t, *J* = 7.3 Hz, 3H), 1.35 (m, 3H), 2.00–2.11 (m, 2H), 2.64 (s, 1H), 5.39 (dt, *J* = 15.6, 6.4 Hz, 1H), 6.54 (d, *J* = 15.6 Hz, 1H), 7.13–7.34 (m, 10H); (minor) δ 0.91 (t, *J* = 7.8 Hz, 3H), 1.47 (s, 3H), 2.00–2.11 (m, 2H), 2.81 (s, 1H), 5.52 (dt, *J* = 15.6, 6.4 Hz, 1H), 6.35 (d, *J* = 15.6 Hz, 1H), 7.13–7.34 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 1.01, 13.5, 21.5, 21.8, 26.1, 26.2, 49.9, 50.0, 81.3 (q, *J* = 25.7 Hz), 81.5 (q, *J* = 25.7 Hz), 126.9, 127.0, 127.1, 127.2, 127.4, 127.5, 127.6, 128.1, 128.2, 128.8, 129.0, 131.4, 131.9, 133.0, 133.5, 136.0, 136.3, 142.2, 142.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ –67.5, –67.0; IR (neat, cm^{-1}) 3552, 3059, 2963, 1955, 1717, 1654, 1600, 1496, 1446, 1377, 1260, 1153, 1062, 1030, 911, 794, 725, 701, 669; HRMS (ESI-TOF) *m/z* calcd. $C_{20}H_{21}F_3NaO$ 357.1442 [M+Na^+]; found: 357.1445.

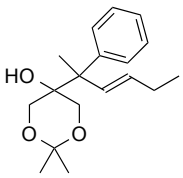


(*E*)-1-(2-Phenylhex-3-en-2-yl)cyclopentanol **9as** (62.7 mg, 0.25 mmol) was obtained in 86% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.94 (t, *J* = 7.4 Hz, 3H), 1.06 (br, 1H), 1.23–1.27 (m, 1H), 1.32–1.37 (m, 1H), 1.42–1.52 (m, 5H), 1.62–1.83 (m, 4H), 2.01–2.08 (m, 2H), 5.50 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.10 (d, *J* = 16.0 Hz, 1H), 7.11–7.15

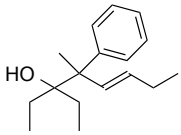
(m, 1H), 7.19–7.24 (m, 2H), 7.40–7.42 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.0, 21.7, 24.0, 24.1, 26.3, 35.8, 36.3, 49.7, 87.0, 126.0, 127.6, 128.4, 132.2, 134.3, 146.0; IR (neat, cm^{-1}) 3461, 2960, 2870, 1719, 1654, 1597, 1542, 1495, 1443, 1374, 1196, 1095, 1000, 906, 758, 701; HRMS (ESI-TOF) *m/z* calcd. $C_{17}H_{24}NaO$ 267.1725 [M+Na^+]; found: 267.1718.



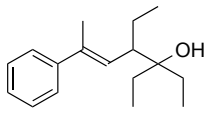
(*E*)-1-(2-Phenylhex-3-en-2-yl)cyclohexanol **9at** (68.0 mg, 0.26 mmol) was obtained in 88% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.90–1.01 (m, 5H), 1.27–1.42 (m, 8H), 1.43 (s, 3H), 1.51 (br, 1H), 2.02–2.09 (m, 2H), 5.46 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.26 (d, *J* = 16.0 Hz, 1H), 7.10–7.14 (m, 1H), 7.19–7.23 (m, 2H), 7.34–7.37 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 20.3, 21.8, 21.9, 25.6, 26.4, 31.9 (2 carbons overlapped), 50.6, 75.0, 125.8, 127.4, 128.8, 131.7, 134.1, 145.7; IR (neat, cm^{-1}) 3567, 2932, 2857, 1685, 1597, 1493, 1444, 1375, 1258, 1127, 1027, 967, 925, 843, 790, 710; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO$ 281.1881 [M+Na^+]; found: 281.1886.



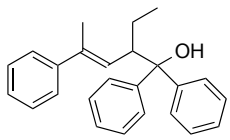
(*E*)-2,2-Dimethyl-5-(2-phenylhex-3-en-2-yl)-1,3-dioxan-5-ol **9au** (71.8 mg, 0.23 mmol) was obtained in 78% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.96 (t, *J* = 7.3 Hz, 3H), 1.27 (s, 3H), 1.30 (s, 3H), 1.45 (s, 3H), 2.04–2.12 (m, 2H), 3.09 (s, 1H), 3.27–3.35 (m, 2H), 3.85 (d, *J* = 11.9 Hz, 1H), 3.93 (d, *J* = 11.9 Hz, 1H), 5.52 (dt, *J* = 16.0, 6.4 Hz, 1H), 6.11 (d, *J* = 16.0 Hz, 1H), 7.10–7.15 (m, 1H), 7.18–7.22 (m, 2H), 7.41–7.44 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 18.3, 20.4, 26.1, 28.5, 46.8, 65.7, 66.0, 70.6, 97.9, 126.3, 127.5, 128.4, 132.1, 132.5, 144.2; IR (neat, cm^{-1}) 3482, 3090, 3055, 2987, 2874, 1740, 1654, 1599, 1494, 1445, 1372, 1293, 1255, 1226, 1201, 1154, 1087, 1054, 1031, 991, 931, 834, 810, 759, 733, 701; HRMS (ESI-TOF) *m/z* calcd. $C_{18}H_{26}NaO_3$ 331.1780 [M+Na^+]; found: 331.1784.



(*E*)-3-Ethyl-4-methyl-4-phenyloct-5-en-3-ol **9av** (28.2 mg, 0.11 mmol) was obtained in 38% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.72 (t, *J* = 7.8 Hz, 3H), 0.75 (t, *J* = 7.4 Hz, 3H), 0.93 (t, *J* = 7.3 Hz, 3H), 1.32–1.44 (m, 2H), 1.45 (s, 3H), 1.47–1.61 (m, 3H), 2.00–2.08 (m, 2H), 5.43 (dt, *J* = 15.6, 6.9 Hz, 1H), 6.25 (d, *J* = 15.6 Hz, 1H), 7.10–7.14 (m, 1H), 7.19–7.23 (m, 2H), 7.38–7.41 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 9.05, 9.23, 13.9, 21.2, 26.3, 27.7, 27.8, 51.4, 77.2, 125.9, 127.5, 128.6, 130.9, 134.9, 146.5; IR (neat, cm^{-1}) 3586, 2963, 1654, 1597, 1542, 1491, 1458, 1376, 1260, 1121, 1028, 960, 761, 702; HRMS (ESI-TOF) *m/z* calcd. $C_{17}H_{26}NaO$ 269.1881 [$M+Na^+$]; found: 269.1877.

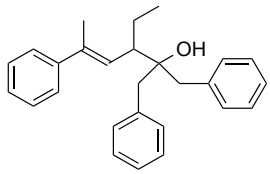


(*E*)-3,4-Diethyl-6-phenylhept-5-en-3-ol **14av** (15.3 mg, 0.06 mmol) was obtained in 21% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.78–0.85 (m, 9H), 1.17–1.27 (m, 2H), 1.44–1.47 (m, 3H), 1.54–1.65 (m, 2H), 2.01 (s, 3H), 2.42–2.48 (m, 1H), 5.59 (d, *J* = 10.5 Hz, 1H), 7.15–7.19 (m, 1H), 7.23–7.27 (m, 2H), 7.33–7.35 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 7.60, 7.75, 12.7, 16.7, 22.4, 28.6, 28.8, 47.5, 76.8, 125.8, 126.8, 128.2, 129.1, 137.6, 144.0; IR (neat, cm^{-1}) 3586, 2965, 1718, 1654, 1560, 1542, 1508, 1491, 1458, 1379, 948, 756, 696; HRMS (ESI-TOF) *m/z* calcd. $C_{17}H_{26}NaO$ 269.1881 [$M+Na^+$]; found: 269.1876.

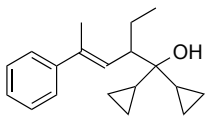


(*E*)-2-Ethyl-1,1,4-triphenylpent-3-en-1-ol **14aw** (56.5 mg, 0.16 mmol) was obtained in 55% yield; white solid of mp = 104–105 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.85 (t, *J* = 7.4 Hz, 3H), 1.19–1.29 (m, 1H), 1.57–1.66 (m, 1H), 1.87 (s, 3H), 3.35 (t, *J* = 10.6 Hz, 1H), 5.52 (d, *J* = 10.6 Hz, 1H), 7.02–7.19 (m, 9H), 7.25–7.34 (m, 5H), 7.46–7.48 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.4, 16.9, 23.7, 48.9, 81.0, 125.8, 125.9, 126.2,

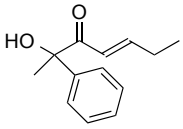
126.4, 126.6, 126.7, 127.7, 128.0, 128.1, 128.2, 137.4, 144.3, 146.3, 146.5; IR (neat, cm^{-1}) 3567, 3056, 2961, 2870, 1706, 1654, 1598, 1542, 1491, 1446, 1377, 1158, 1031, 877, 757, 698; HRMS (ESI-TOF) *m/z* calcd. $C_{25}H_{26}NaO$ 365.1881 [M+Na^+]; found: 365.1884.



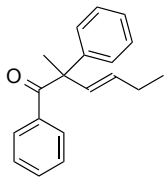
(*E*)-2-Benzyl-3-ethyl-1,5-diphenylhex-4-en-2-ol **14ax** (65.8 mg, 0.17 mmol) was obtained in 58% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.71 (t, *J* = 7.3 Hz, 3H), 1.29–1.41 (m, 1H), 1.64 (s, 3H), 1.70 (br, 1H), 1.77–1.88 (m, 1H), 2.28–2.34 (m, 1H), 2.78–2.87 (m, 4H), 5.45 (d, *J* = 10.6 Hz, 1H), 7.15–7.24 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.6, 16.6, 23.7, 43.1, 43.8, 48.0, 76.9, 125.8, 126.2, 126.3, 126.9, 127.9, 128.0, 128.1, 128.2, 130.8, 130.9, 137.7, 137.8, 139.8, 143.7; IR (neat, cm^{-1}) 3548, 3082, 3059, 3026, 2959, 2871, 1945, 1878, 1803, 1719, 1601, 1493, 1453, 1378, 1284, 1181, 1155, 1125, 1081, 1030, 940, 925, 873, 782, 755, 699; HRMS (ESI-TOF) *m/z* calcd. $C_{27}H_{30}NaO$ 393.2194 [M+Na^+]; found: 393.2196.



(*E*)-1,1-Dicyclopropyl-2-ethyl-4-phenylpent-3-en-1-ol **14ay** (21.9 mg, 0.08 mmol) was obtained in 27% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.18–0.47 (m, 8H), 0.73–0.79 (m, 1H), 0.82 (t, *J* = 7.8 Hz, 3H), 0.94–1.01 (m, 2H), 1.32–1.43 (m, 1H), 1.85–1.94 (m, 1H), 2.02 (s, 3H), 2.52–2.58 (m, 1H), 5.69 (d, *J* = 10.6 Hz, 1H), 7.15–7.17 (m, 1H), 7.23–7.28 (m, 2H), 7.32–7.35 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ -0.69, 0.37, 1.00, 1.64, 12.8, 16.0, 16.6, 17.5, 23.1, 53.3, 72.6, 125.7, 126.7, 128.2, 129.8, 137.7, 144.0; IR (neat, cm^{-1}) 3586, 3006, 2961, 2928, 2870, 1654, 1560, 1542, 1509, 1491, 1458, 1379, 1261, 1020, 911, 799, 758, 696; HRMS (ESI-TOF) *m/z* calcd. $C_{19}H_{26}NaO$ 293.1881 [M+Na^+]; found: 293.1878.



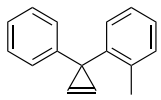
(*E*)-2-Hydroxy-2-phenylhept-4-en-3-one **10r** (11.6 mg, 0.05 mmol) was obtained in 19% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.92 (t, *J* = 7.3 Hz, 3H), 1.70 (s, 3H), 2.06–2.14 (m, 2H), 4.71 (s, 1H), 6.11 (d, *J* = 15.1 Hz, 1H), 7.05 (dt, *J* = 15.1, 6.9 Hz, 1H), 7.21–7.38 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.1, 24.0, 25.8, 78.6, 121.7, 126.3, 128.0, 128.6, 141.4, 152.5, 199.6; IR (neat, cm^{-1}) 3447, 2970, 2933, 1685, 1624, 1492, 1447, 1367, 1287, 1220, 1139, 1067, 1007, 978, 914, 861, 760, 699; HRMS (ESI-TOF) *m/z* calcd. $C_{13}H_{16}NaO_2$ 227.1048 [M+Na^+]; found: 227.1052.



(*E*)-2-Methyl-1,2-diphenylhex-3-en-1-one **15** (33.1 mg, 0.12 mmol) was obtained in 42% yield; colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (t, *J* = 7.3 Hz, 3H), 1.56 (s, 3H), 1.97–2.05 (m, 2H), 5.55 (dt, *J* = 15.6, 6.4 Hz, 1H), 5.87 (d, *J* = 15.6 Hz, 1H), 7.12–7.30 (m, 8H), 7.46–7.48 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.7, 26.1, 27.2, 57.6, 126.4, 126.7, 127.8, 128.9, 130.1, 131.5, 131.7, 134.6, 136.2, 145.4, 201.1; IR (neat, cm^{-1}) 3024, 2964, 2931, 1678, 1596, 1577, 1491, 1446, 1371, 1232, 1181, 1076, 1027, 972, 909, 853, 763, 700; HRMS (ESI-TOF) *m/z* calcd. $C_{19}H_{20}NaO$ 287.1412 [M+Na^+]; found: 287.1421.

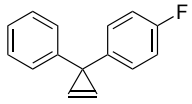
Synthesis of Substrate

Cyclopropene substrates were synthesized from ketones for 4 steps. [S1]

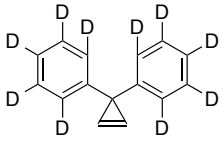


1-Methyl-2-(1-phenylcycloprop-2-en-1-yl)benzene **8j** (185 mg, 0.9 mmol) was obtained in 6% yield (4 steps); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.10 (s, 3H), 6.88–6.91 (m, 2H), 7.03–7.21 (m, 7H), 7.45 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.4,

30.8, 113.6, 125.1, 126.3, 126.6 (2 carbons overlapped), 127.8, 129.1, 130.4, 137.2, 144.1, 148.1; IR (neat, cm^{-1}) 3567, 2923, 1719, 1638, 1598, 1542, 1509, 1490, 1445, 1136, 902, 749, 728, 698; HRMS (APCI) *m/z* calcd. $C_{16}H_{14}$ 206.1096 [M^+]; found: 206.1094.

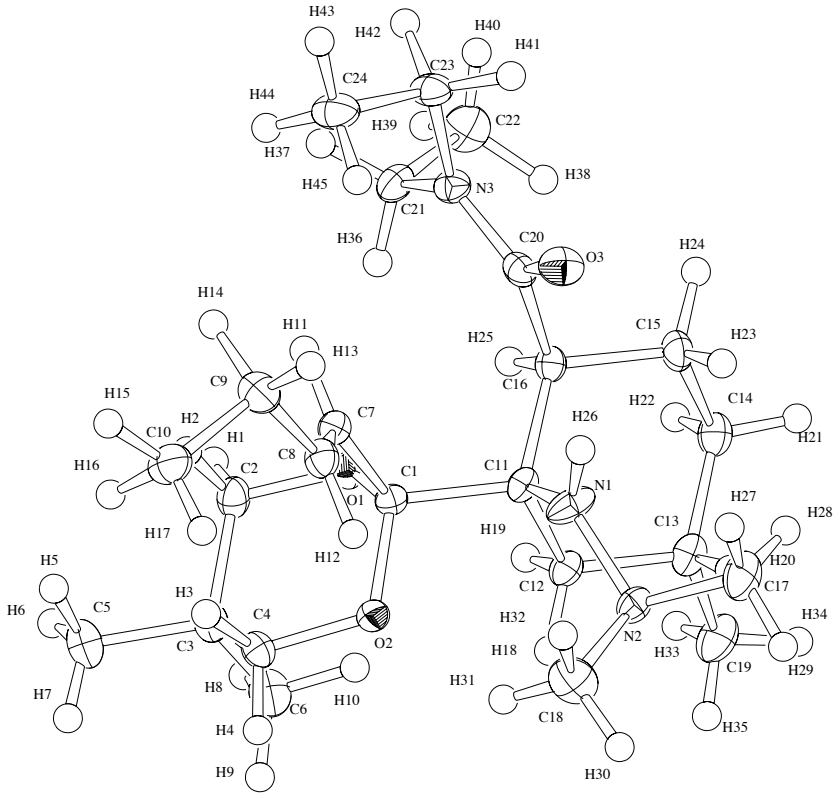


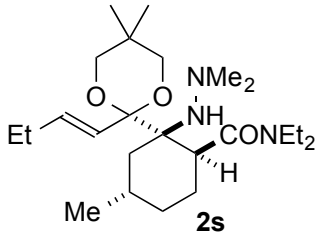
1-Fluoro-4-(1-phenylcycloprop-2-en-1-yl)benzene **8k** (506 mg, 2.4 mmol) was obtained in 32% yield (4 steps); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.99–7.06 (m, 2H), 7.18–7.28 (m, 5H), 7.33–7.37 (m, 2H), 7.52 (s, 1H), 7.53 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ ; 31.2, 113.3, 114.8 (d, J = 21.0 Hz), 125.8, 127.9, 128.1, 129.5 (d, J = 7.6 Hz), 142.7, 146.9, 161.1 (d, J = 243 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ –117.23; IR (neat, cm^{-1}) 3100, 3056, 3023, 2926, 1892, 1640, 1599, 1507, 1491, 1445, 1286, 1224, 1157, 1094, 1074, 1014, 992, 900, 854, 810, 754, 700, 671; HRMS (ESI-TOF) *m/z* calcd. $C_{15}H_{12}F_2$ 211.0923 [M+H^+]; found: 211.0921.



3-(Phenyl-d_5)-1*H*-indene-1,4,5,6,7-d_5 ***d*-8b** (933 mg, 4.6 mmol) was obtained in 46% yield (4 steps); colorless oil; H NMR (400 MHz, $CDCl_3$) δ 7.55 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) d 31.6, 113.2, 125.2 (t, J = 24.8 Hz), 127.5 (t, J = 23.8 Hz), 127.6 (t, J = 22.9 Hz), 146.9; IR (neat, cm^{-1}) 3134, 3098, 2926, 2273, 1719, 1640, 1566, 1437, 1369, 1325, 1281, 1206, 1063, 991, 901, 862, 823, 751; HRMS (ESI-TOF) *m/z* calcd. $C_{15}H_3D_{10}$ 203.1645 [M+H^+]; found: 203.1641.

X-ray Structure Report





2s

Experimental

Data Collection

A Colorless Prism crystal of $H_{45}C_{24}N_3O_3$ having approximate dimensions of 0.45 x 0.30 x 0.15 mm was mounted in a loop. All measurements were made on a Rigaku/MSC Mercury diffractometer with graphite monochromated Mo-Kα radiation.

Cell constants and an orientation matrix for data collection corresponded to a primitive orthorhombic cell with dimensions:

a = 10.670(1) Å
b = 14.524(2) Å
c = 16.368(3) Å
V = 2536.6(6) $Å^3$

For Z = 4 and F.W. = 423.64, the calculated density is 1.11 g/cm^3. The systematic absences of:

h00: h ± 2n
0k0: k ± 2n
00l: l ± 2n

uniquely determine the space group to be:

$P2_12_12_1$ (#19)

The data were collected at a temperature of -190 ± 1°C to a maximum 2θ value of 55.0°.A total of 720 oscillation images were collected. A first sweep of data was done using ω scans from -80.0 to 100.0° in 0.50° step, at χ=45.0° and φ=0.0°. The exposure rate was 34.0 [sec./°]. The detector swing angle was 10.0°. The crystal-to-detector distance was 34.92 mm. A second sweep of data was done using ω scans from -80.0 to 100.0° in 0.50° step, at χ=45.0° and φ=90.0°. The exposure rate was 34.0 [sec./°]. The detector swing angle was 10.0°. The crystal-to-detector distance was 34.92 mm.

Data Reduction

Of the 3269 reflections which were collected, 3246 were unique (R_{int} = 0.042); equivalent reflections were merged. Data were collected and processed using the CrystalClear program (Rigaku). The linear absorption coefficient, μ, for Mo-Kα radiation is 0.7 cm^{-1}. was applied which resulted in transmission factors ranging from 0.74 to 0.99. The data were corrected for Lorentz and polarization effects.

Structure Solution and Refinement

The structure was solved by direct methods[1] and expanded using Fourier techniques[2]. The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement[3] was based on 4792 observed reflections ($I > 3.00\sigma(I)$, $2\theta < 0.00$) and 272 variable parameters and converged (largest parameter shift was 0.01 times its esd) with unweighted and weighted agreement factors of:

$$R = \Sigma \, ||Fo| - |Fc|| \, / \, \Sigma \, |Fo| = 0.041$$

$$R_W = [(\Sigma \, w \, (|Fo| - |Fc|)^2 \, / \, \Sigma \, w \, Fo^2)]^{1/2} = 0.054$$

The standard deviation of an observation of unit weight[4] was 1.16. The weighting scheme was based on counting statistics and included a factor ($p = 0.050$) to downweight the intense reflections. Plots of $\Sigma \, w \, (|Fo| - |Fc|)^2$ versus $|Fo|$, reflection order in data collection, $\sin\theta/\lambda$ and various classes of indices showed no unusual trends. The maximum and minimum peaks on the final difference Fourier map corresponded to 0.33 and -0.18 $e^-/Å^3$, respectively.

Neutral atom scattering factors were taken from Cromer and Waber[5]. Anomalous dispersion effects were included in Fcalc[6]; the values for $\Delta f'$ and $\Delta f''$ were those of Creagh and McAuley[7]. The values for the mass attenuation coefficients are those of Creagh and Hubbel[8]. All calculations were performed using the teXsan[9] crystallographic software package of Molecular Structure Corporation.

References

(1) SIR92: Altomare, A., Burla, M.C., Camalli, M., Cascarano, M., Giacovazzo, C., Guagliardi, A., Polidori, G., (1994). J. Appl. Cryst. 27, 435.

(2) DIRDIF94: Beurskens, P.T., Admiraal, G., Beurskens, G., Bosman, W.P., de Gelder, R., Israel, R. and Smits, J.M.M.(1994). The DIRDIF-94 program system, Technical Report of the Crystallography Laboratory, University of Nijmegen, The Netherlands.

(3) Least-Squares:

Function minimized: $\Sigma \, w(|F_o|-|F_c|)^2$ where
$w = 1/[\sigma^2(Fo)] = [\sigma^2_c(Fo) + p^2Fo^2/4]^{-1}$

σ_c(Fo) = e.s.d. based on counting statistics
p = p-factor

(4) Standard deviation of an observation of unit weight:

$$[\Sigma\, w(|F_o|-|F_c|)^2/(N_o-N_v)]^{1/2}$$

where: N_o = number of observations
N_v = number of variables

(5) Cromer, D. T. & Waber, J. T.; "International Tables for X-ray Crystallography", Vol. IV, The Kynoch Press, Birmingham, England, Table 2.2 A (1974).

(6) Ibers, J. A. & Hamilton, W. C.; Acta Crystallogr., 17, 781 (1964).

(7) Creagh, D. C. & McAuley, W.J .; "International Tables for Crystallography", Vol C, (A.J.C. Wilson, ed.), Kluwer Academic Publishers, Boston, Table 4.2.6.8, pages 219-222 (1992).

(8) Creagh, D. C. & Hubbell, J.H..; "International Tables for Crystallography", Vol C, (A.J.C. Wilson, ed.), Kluwer Academic Publishers, Boston, Table 4.2.4.3, pages 200-206 (1992).

(9) teXsan: Crystal Structure Analysis Package, Molecular Structure Corporation (1985 & 1999).

EXPERIMENTAL DETAILS

A. Crystal Data

Empirical Formula	$H_{45}C_{24}N_3O_3$
Formula Weight	423.64
Crystal Color, Habit	Colorless, Prism
Crystal Dimensions	0.45 X 0.30 X 0.15 mm
Crystal System	orthorhombic
Lattice Type	Primitive
No. of Reflections Used for Unit Cell Determination (2θ range)	12561 (6.1 - 55.0°)
Lattice Parameters	a = 10.670(1) Å b = 14.524(2) Å c = 16.368(3) Å V = 2536.6(6) $Å^3$
Space Group	$P2_12_12_1$ (#19)
Z value	4
D_{calc}	1.109 g/cm^3
F_{000}	936.00
μ(MoKα)	0.73 cm^{-1}

B. Intensity Measurements

Diffractometer	Rigaku/MSC Mercury CCD
Radiation	MoKα (λ = 0.71070 Å) graphite monochromated

Temperature	-190.0 °C
Detector Aperture	70 mm x 70 mm
Data Images	720 exposures
ω oscillation Range (χ=45.0, φ=0.0) ω oscillation Range (χ=45.0, φ=90.0)	-80.0 - 100.0° -80.0 - 100.0°
Exposure Rate	34.0 sec./°
Detector Swing Angle	10.01°
Detector Position	34.92 mm
$2\theta_{max}$	55.0°
No. of Reflections Measured	Total: 3269 Unique: 3246 (R_{int} = 0.042)
Corrections	Lorentz-polarization Absorption (trans. factors: 0.7379 - 0.9892)

C. Structure Solution and Refinement

Structure Solution	Direct Methods (SIR92)
Refinement	Full-matrix least-squares
Function Minimized	Σ w (|Fo| - |Fc|)^2
Least Squares Weights	$1/\sigma^2(Fo) = 4Fo^2/\sigma^2(Fo^2)$
p-factor	0.0500

Anomalous Dispersion	All non-hydrogen atoms
No. of Observations ($I>3.00\sigma(I)$, $2\theta < 0.00^{o}$)	4792
No. Variables	272
Reflection/Parameter Ratio	17.62
Residuals: R; Rw	0.041 ; 0.054
Goodness of Fit Indicator	1.16
Max Shift/Error in Final Cycle	0.009
Maximum peak in Final Diff. Map	0.33 $e^{-}/Å^{3}$
Minimum peak in Final Diff. Map	-0.18 $e^{-}/Å^{3}$

Table 1. Atomic coordinates and B_{iso}/B_{eq}

atom	x	y	z	B_{eq}
O(1)	0.2568(1)	-0.00323(9)	0.63248(6)	1.35(2)
O(2)	0.1167(1)	-0.12193(8)	0.60044(7)	1.31(2)
O(3)	-0.0465(1)	0.18704(9)	0.54948(7)	1.90(2)
N(1)	-0.0858(1)	0.0068(1)	0.61475(9)	1.99(3)
N(2)	-0.1721(1)	-0.0557(1)	0.65171(9)	1.49(3)
N(3)	0.1542(1)	0.2333(1)	0.56063(8)	1.46(3)
C(1)	0.1390(1)	-0.0255(1)	0.59589(9)	1.17(3)
C(2)	0.3596(2)	-0.0528(1)	0.5980(1)	1.64(3)
C(3)	0.3411(2)	-0.1568(1)	0.6043(1)	1.60(3)
C(4)	0.2142(2)	-0.1769(1)	0.56484(10)	1.46(3)
C(5)	0.4442(2)	-0.2057(1)	0.5563(1)	2.13(4)
C(6)	0.3408(2)	-0.1878(1)	0.6936(1)	2.13(4)
C(7)	0.1391(2)	0.0072(1)	0.50804(9)	1.47(3)
C(8)	0.0687(2)	-0.0298(1)	0.44971(10)	1.59(3)
C(9)	0.0724(2)	-0.0032(1)	0.3608(1)	2.02(3)
C(10)	0.0929(2)	-0.0871(1)	0.3060(1)	2.14(4)
C(11)	0.0373(1)	0.0207(1)	0.65261(9)	1.25(3)
C(12)	0.0465(2)	-0.0246(1)	0.73763(9)	1.41(3)
C(13)	-0.0316(2)	0.0208(1)	0.80443(10)	1.69(3)
C(14)	-0.0050(2)	0.1240(1)	0.8101(1)	1.82(3)
C(15)	-0.0200(2)	0.1703(1)	0.7269(1)	1.66(3)
C(16)	0.0670(1)	0.1252(1)	0.66297(10)	1.31(3)
C(17)	-0.2921(2)	-0.0099(1)	0.6638(1)	2.19(4)
C(18)	-0.1881(2)	-0.1366(1)	0.6003(1)	2.50(4)
C(19)	-0.0061(2)	-0.0276(2)	0.8855(1)	2.33(4)
C(20)	0.0553(2)	0.1828(1)	0.58568(9)	1.39(3)
C(21)	0.2799(2)	0.2312(1)	0.5974(1)	1.76(3)
C(22)	0.2946(2)	0.3006(1)	0.6664(1)	2.40(4)
C(23)	0.1380(2)	0.2954(1)	0.4903(1)	1.79(3)
C(24)	0.1563(2)	0.2465(1)	0.4087(1)	2.19(4)
H(1)	0.4362	-0.0229	0.6242	7.2
H(2)	0.3694	-0.0340	0.5387	7.2
H(3)	0.2253	-0.1679	0.5040	7.2
H(4)	0.1900	-0.2403	0.5743	7.2
H(5)	0.4416	-0.1765	0.5005	7.2
H(6)	0.5275	-0.1915	0.5793	7.2
H(7)	0.4330	-0.2692	0.5559	7.2
H(8)	0.4219	-0.1735	0.7225	7.2
H(9)	0.3187	-0.2574	0.6955	7.2
H(10)	0.2691	-0.1470	0.7197	7.2
H(11)	0.1976	0.0616	0.4936	7.2
H(12)	0.0090	-0.0826	0.4637	7.2
H(13)	-0.0086	0.0248	0.3427	7.2
H(14)	0.1537	0.0416	0.3505	7.2
H(15)	0.0255	-0.1290	0.3126	2.6
H(16)	0.0973	-0.0679	0.2505	2.6
H(17)	0.1693	-0.1166	0.3206	2.6

H(18)	0.0299	-0.0944	0.7355	7.2
H(19)	0.1301	-0.0201	0.7557	7.2
H(20)	-0.1170	0.0133	0.7866	7.2
H(21)	-0.0603	0.1589	0.8496	7.2
H(22)	0.0877	0.1345	0.8341	7.2
H(23)	-0.1167	0.1647	0.7036	7.2
H(24)	-0.0010	0.2390	0.7337	7.2
H(25)	0.1517	0.1233	0.6845	7.2
H(26)	-0.1175	0.0474	0.5804	7.2
H(27)	-0.3252	0.0171	0.6061	7.2
H(28)	-0.2847	0.0410	0.7002	7.2
H(29)	-0.3509	-0.0556	0.6870	7.2
H(30)	-0.2507	-0.1777	0.6249	7.2
H(31)	-0.1102	-0.1665	0.5925	7.2
H(32)	-0.2267	-0.1122	0.5419	7.2
H(33)	0.0774	-0.0222	0.9028	7.2
H(34)	-0.0550	-0.0066	0.9360	7.2
H(35)	-0.0268	-0.0923	0.8859	7.2
H(36)	0.2926	0.1673	0.6165	7.2
H(37)	0.3425	0.2417	0.5512	7.2
H(38)	0.2283	0.2819	0.7160	7.2
H(39)	0.3800	0.2982	0.6871	7.2
H(40)	0.2815	0.3593	0.6396	7.2
H(41)	0.0412	0.3223	0.4952	7.2
H(42)	0.2118	0.3452	0.4961	7.2
H(43)	0.1503	0.2917	0.3610	7.2
H(44)	0.2392	0.2194	0.4045	7.2
H(45)	0.0920	0.1944	0.4058	7.2

$B_{eq} = 8/3\ \pi^2(U_{11}(aa^*)^2 + U_{22}(bb^*)^2 + U_{33}(cc^*)^2 + 2U_{12}(aa^*bb^*)\cos\gamma + 2U_{13}(aa^*cc^*)\cos\beta + 2U_{23}(bb^*cc^*)\cos\alpha)$

Table 2. Anisotropic Displacement Parameters

atom	U_{11}	U_{22}	U_{33}	U_{12}	U_{13} U_{23}
O(1)	0.0122(5)	0.0202(6)	0.0190(5)	-0.0018(5)	-0.0001(4) -0.0043(5)
O(2)	0.0159(6)	0.0157(6)	0.0182(5)	-0.0007(4)	0.0011(4) 0.0009(5)
O(3)	0.0222(6)	0.0236(7)	0.0262(6)	0.0000(5)	-0.0070(5) 0.0036(5)
N(1)	0.0158(7)	0.0316(9)	0.0281(7)	-0.0087(6)	-0.0061(6) 0.0133(7)
N(2)	0.0131(6)	0.0219(8)	0.0217(6)	-0.0037(5)	0.0008(5) 0.0008(6)
N(3)	0.0226(7)	0.0183(7)	0.0146(6)	-0.0006(6)	-0.0004(5) 0.0019(5)
C(1)	0.0142(7)	0.0149(7)	0.0153(7)	-0.0015(6)	-0.0014(6) 0.0002(6)
C(2)	0.0146(8)	0.0244(8)	0.0231(8)	-0.0015(6)	0.0013(7) -0.0050(7)
C(3)	0.0185(8)	0.0232(8)	0.0190(7)	0.0028(7)	-0.0004(6) -0.0011(7)
C(4)	0.0193(8)	0.0186(9)	0.0175(8)	0.0019(7)	0.0000(6) -0.0028(6)
C(5)	0.0241(9)	0.031(1)	0.0261(9)	0.0072(8)	0.0000(7) -0.0053(8)
C(6)	0.0276(9)	0.033(1)	0.0198(7)	0.0074(8)	-0.0048(7) 0.0019(7)
C(7)	0.0215(8)	0.0178(8)	0.0165(7)	-0.0001(7)	0.0037(6) 0.0005(6)
C(8)	0.0224(8)	0.0227(9)	0.0154(7)	0.0029(7)	0.0003(6) -0.0007(6)
C(9)	0.036(1)	0.0246(9)	0.0165(7)	0.0053(8)	-0.0020(7) 0.0015(6)
C(10)	0.036(1)	0.0261(10)	0.0195(8)	-0.0060(8)	0.0029(7) -0.0020(7)
C(11)	0.0143(7)	0.0201(8)	0.0133(6)	-0.0013(6)	0.0004(6) 0.0013(6)
C(12)	0.0182(8)	0.0215(9)	0.0137(6)	-0.0008(7)	0.0004(6) 0.0017(6)
C(13)	0.0182(8)	0.0280(9)	0.0180(7)	-0.0011(7)	0.0007(6) 0.0007(7)
C(14)	0.0233(8)	0.0284(9)	0.0175(7)	0.0017(7)	0.0028(7) -0.0026(7)
C(15)	0.0220(9)	0.0237(9)	0.0175(7)	0.0039(7)	0.0032(6) -0.0022(6)
C(16)	0.0140(7)	0.0198(8)	0.0159(7)	0.0012(6)	0.0000(6) -0.0006(6)
C(17)	0.0145(8)	0.038(1)	0.0300(9)	0.0021(8)	0.0002(7) 0.0026(9)

C(18)	0.0274(10)	0.029(1)	0.038(1)	-0.0043(8)	-0.0067(8)
	-0.0084(9)				
C(19)	0.0312(10)	0.041(1)	0.0163(8)	-0.0012(9)	0.0028(7)
	0.0054(8)				
C(20)	0.0210(8)	0.0161(8)	0.0158(7)	0.0028(6)	0.0003(6)
	-0.0021(6)				
C(21)	0.0193(8)	0.0243(9)	0.0233(8)	-0.0033(7)	0.0022(7)
	0.0028(7)				
C(22)	0.0287(10)	0.033(1)	0.0290(9)	-0.0062(9)	-0.0041(8)
	-0.0044(8)				
C(23)	0.0339(10)	0.0173(9)	0.0168(7)	-0.0019(7)	0.0002(7)
	0.0031(6)				
C(24)	0.044(1)	0.0214(10)	0.0175(7)	-0.0043(8)	0.0009(8)
	0.0011(6)				

The general temperature factor expression:
$\exp(-2\pi^2(a^{*2}U_{11}h^2 + b^{*2}U_{22}k^2 + c^{*2}U_{33}l^2 + 2a^*b^*U_{12}hk + 2a^*c^*U_{13}hl + 2b^*c^*U_{23}kl))$

Table 3. Bond Lengths(Å)

atom	atom	distance	atom	atom	distance
O1	C1	1.430(2)	O1	C2	1.428(2)
O2	C1	1.423(2)	O2	C4	1.435(2)
O3	C20	1.239(2)	N1	N2	1.428(2)
N1	C11	1.466(2)	N2	C17	1.456(2)
N2	C18	1.456(3)	N3	C20	1.349(2)
N3	C21	1.470(2)	N3	C23	1.473(2)
C1	C7	1.514(2)	C1	C11	1.578(2)
C2	C3	1.526(3)	C3	C4	1.527(2)
C3	C5	1.527(3)	C3	C6	1.530(3)
C7	C8	1.328(3)	C8	C9	1.506(2)
C9	C10	1.529(3)	C11	C12	1.542(2)
C11	C16	1.560(3)	C12	C13	1.525(3)
C13	C14	1.527(3)	C13	C19	1.527(3)
C14	C15	1.527(3)	C15	C16	1.545(2)
C16	C20	1.522(2)	C21	C22	1.523(3)
C23	C24	1.526(3)			

Table 4. Bond Angles(°)

atom	atom	atom	angle	atom	atom	atom	angle
C1	O1	C2	113.3(1)	C1	O2	C4	113.9(1)
N2	N1	C11	119.1(1)	N1	N2	C17	109.6(2)
N1	N2	C18	110.1(2)	C17	N2	C18	110.1(2)
C20	N3	C21	125.3(1)	C20	N3	C23	118.6(2)
C21	N3	C23	116.1(1)	O1	C1	O2	110.3(1)
O1	C1	C7	109.1(1)	O1	C1	C11	105.2(1)
O2	C1	C7	111.0(1)	O2	C1	C11	105.8(1)
C7	C1	C11	115.2(1)	O1	C2	C3	111.9(1)
C2	C3	C4	106.0(1)	C2	C3	C5	109.4(2)
C2	C3	C6	110.8(2)	C4	C3	C5	109.4(1)
C4	C3	C6	110.2(2)	C5	C3	C6	110.8(2)
O2	C4	C3	111.4(1)	C1	C7	C8	123.8(2)
C7	C8	C9	125.2(2)	C8	C9	C10	111.5(2)
N1	C11	C1	108.0(1)	N1	C11	C12	112.4(1)
N1	C11	C16	111.2(1)	C1	C11	C12	107.8(1)
C1	C11	C16	109.7(1)	C12	C11	C16	107.7(1)
C11	C12	C13	115.3(2)	C12	C13	C14	111.5(2)
C12	C13	C19	109.1(2)	C14	C13	C19	111.5(2)
C13	C14	C15	111.0(2)	C14	C15	C16	110.7(2)
C11	C16	C15	111.4(1)	C11	C16	C20	115.3(1)
C15	C16	C20	106.3(1)	O3	C20	N3	120.9(2)
O3	C20	C16	119.8(2)	N3	C20	C16	119.2(2)
N3	C21	C22	112.6(2)	N3	C23	C24	112.6(2)

Table 5. Non-bonded Contacts out to 3.60 Å

atom	atom	distance	atom	atom
	distance			
O1	C10[1)]	3.515(2)	O3	C21[2)]
	3.259(2)			
O3	C24[2)]	3.385(3)	O3	C23[2)]
	3.438(2)			
C19	C23[3)]	3.567(3)		

Symmetry operations

(1) -X+1/2,-Y,Z+1/2 (2) X-1/2,-Y+1/2,-Z+1
(3) -X,Y-1/2,-Z+3/2

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