# Nickel-Catalyzed Intermolecular [3 + 2 + 2] Cocyclization of Ethyl Cyclopropylideneacetate and Alkynes. Synthesis of Seven-Membered Carbocycles

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*Received July 14, 2007*

The [3 + 2 + 2] cocyclization of ethyl cyclopropylideneacetate (**1a**) and various alkynes proceeded smoothly in the presence of Ni(cod)$_2$–PPh$_3$. The cycloheptadiene derivatives were synthesized in highly selective manners. The unique reactivity of **1a** was essential for the progress of the reaction. The observed regioselectivity of the product formation and the mechanism of the reaction are discussed.

## Introduction

Transition metal-catalyzed cycloaddition reactions provided efficient pathways for the synthesis of cyclic compounds.[1] Especially, intermolecular cycloaddition is an attractive approach, since a complicated molecule can be constructed in a few steps from readily available compounds. While a number of reactions are available for the synthesis of three- to six-membered rings, fewer methods have been reported for the catalytic synthesis of seven-membered carbocycles. The [4 + 3],[2] [5 + 2],[3] [3 + 2 + 2],[4] and other[5] cycloadditions have been reported, and some reactions have been applied to the synthesis of various seven-membered carbocycles including a variety of natural products.[6]

We recently studied the substituent effects on the nickel-catalyzed reactions of unsaturated hydrocarbons[7] and revealed that the mode of the reaction changed completely when an electron-deficient hydrocarbon was used as the substrate.[8] For

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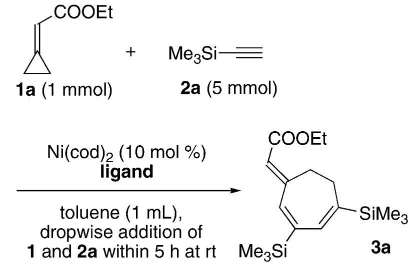
10.1021/jo7014714 CCC: $37.00

example, the nickel-catalyzed reaction of alkylallenes resulted in the formation of a complex mixture of dimers, trimers, and oligomers,[9] while the selective [2 + 2] cyclodimerization was observed when an electron-deficient allene was used as the substrate.[10] Ethyl cyclopropylideneacetate (**1a**),[11] an electron-deficient methylenecyclopropane, was more reactive compared to alkylidenecyclopropanes and the dimerization proceeded smoothly in the presence of Ni(0) catalysts.[12] We also examined the reactions of electron-deficient methylenecyclopropanes with unsaturated hydrocarbons. Though the [3 + 2] cycloaddition was generally observed when the reaction of methylenecyclopropanes with alkenes or alkynes was carried out in the presence of a Ni or a Pd catalyst,[2h,i,13] the selective formation of cycloheptadienes was observed when the reaction of an electron-deficient methylenecyclopropane with alkynes was carried out in the presence of Ni(cod)$_2$–PPh$_3$.[14] In this paper, we describe the details and mechanistic aspects of this new [3 + 2 + 2] cocyclization reaction.

**TABLE 1. Screening of the Reaction Conditions and Ligands for the Nickel-Catalyzed [3 + 2 + 2] Cocyclization of 1a and 2a**[a]



| entry | ligand | amount (mol %) | time (h)[b] | **3a** (% yield)[c] |
|---|---|---|---|---|
| 1 | PPh$_3$ | 20 | 14.5 | 70 |
| 2[d] | PPh$_3$ | 20 | 42 | 72 |
| 3 | PPh$_3$ | *e* | 61 | 21 |
| 4 | PPh$_3$ | 10 | 21 | 48 |
| 5 | PPh$_3$ | 40 | 14 | 59 |
| 6[f] | PPh$_3$ | 20 | 23 | 8 |
| 7[g] | PPh$_3$ | 40 | 19.5 | 56 |
| 8 | P(*o*-tol)$_3$ | 20 | 19 | 46 |
| 9 | PEt$_3$ | 20 | 39 | 18 |
| 10 | P(*t*-Bu)$_3$ | 20 | 37.5 | 0 |
| 11 | P(*n*-Bu)$_3$ | 20 | 24 + 43[h] | 12 |
| 12 | PCy$_3$ | 20 | 43 | 2 |
| 13 | P(OPh)$_3$ | 20 | 42 | 14 |
| 14 | P(C$_6$F$_5$)$_3$ | 20 | 2.5 + 19[h] | (9)[i] |
| 15 | TOPP[j] | 10 | 22 + 20[h] | 17 |
| 16 | dppe | 10 | 43 | 20 |
| 17 | dppf | 10 | 22 | 13 |
| 18 | none | | 48 | 0 |
| 19 | PPh$_3$[k] | 20 | 17.5 | 57 |
| 20 | PPh$_3$[l] | 20 | 9.5 | 47 |
| 21 | PPh$_3$[m] | 20 | 19 | 70 |
| 22 | PPh$_3$[n] | 20 | 20 | 62 |
| 23 | PPh$_3$[o] | 20 | 20.5 | 66 |
| 24 | PPh$_3$[p] | 20 | 19 | 65 |
| 25 | PPh$_3$[q] | 20 | 21.5 | 52 |
| 26 | PPh$_3$[r] | 20 | 26 | 18 |
| 27 | PPh$_3$[s] | 20 | 18.5 | *i* |
| 28 | PPh$_3$[t] | 20 | 26 | *i* |

[a] Reaction conditions: to a mixture of Ni(cod)$_2$ (0.1 mmol) and ligand in toluene (0.5 mL) was added dropwise a solution of **1a** (1 mmol) and **2a** (5 mmol) in toluene (0.5 mL) at rt within 5 h under Ar. [b] After dropwise addition of **1a** and **2a**, the reaction mixture was stirred for the specified period. [c] Isolated yields. [d] The reaction was carried out on a 15 mmol (**1a**) scale. [e] The reaction was carried out in the presence of Ni(cod)$_2$ (0.05 mmol) and PPh$_3$ (0.10 mmol). [f] The catalyst was prepared by mixing Ni(PPh$_3$)$_2$Br$_2$ (0.1 mmol) and Zn dust (1 mmol) in toluene (0.5 mL). [g] The catalyst was prepared by mixing Ni(PPh$_3$)$_2$Br$_2$ (0.1 mmol), PPh$_3$ (0.2 mmol), and Zn dust (1 mmol) in toluene (0.5 mL). [h] After being stirred at rt, the reaction mixture was heated (50 °C) for the specified period. [i] An inseparable mixture of isomers was isolated. [j] TOPP = tri-*o*-biphenyl phosphite. [k] A smaller amount of **2a** (3 mmol) was used. [l] Addition of a solution of **1a** and **2a** within 10 h. [m] Addition of a solution of **1a** and **2a** within 3 h. [n] Addition of a solution of **1a** and **2a** at once. [o] Reaction performed in MeCN. [p] Reaction performed in THF. [q] Reaction performed in ether. [r] Reaction performed in CH$_2$Cl$_2$. [s] Reaction performed in DMF. [t] Reaction performed in DMSO.

## Results and Discussion

**Screening of the Reaction Conditions for the [3 + 2 + 2] Cocyclization.** The results of the screening of the reaction conditions and ligands for the [3 + 2 + 2] cocyclization reaction are summarized in Table 1. Slow addition of a solution of ethyl cyclopropylideneacetate (**1a**) and trimethylsilylacetylene (**2a**, 5 equiv) to a solution of Ni(cod)$_2$ (10 mol %) and PPh$_3$ (20 mol %) in toluene at rt afforded the [3 + 2 + 2] cocyclization product **3a** in 70% yield (entry 1, Table 1). The slow addition of both **1a** and **2a** and the use of an excess (5 equiv) of **2a** were necessary to obtain **3a** in good yield.[14a] The yield of **3a** remained essentially unchanged when the reaction was carried out at 15 mmol scale (entry 2). When the reaction was carried out in the presence of a smaller amount of Ni(cod)$_2$ and PPh$_3$, compound **3a** was isolated in low yield (entry 3). The yield of **3a** also decreased with the addition of a larger amount (40 mol %) or a smaller amount (10 mol %) of PPh$_3$ (entries 4 and 5). The yield of **3a** was low when the catalyst was prepared in situ from Ni(PPh$_3$)$_2$Br$_2$ and Zn dust[15] (entry 6), while an acceptable yield of **3a** was observed when the Ni(PPh$_3$)$_2$Br$_2$−Zn−PPh$_3$ system[15a] was used (entry 7). The product (**3a**) was isolated in 46% yield when P(*o*-tol)$_3$ was selected as the phosphine ligand (entry 8). On the other hand, the isolated yield of **3a** was low when other readily available phosphine ligands such as PEt$_3$, P(OPh)$_3$, and P(C$_6$F$_5$)$_3$ were used (entries 9−14). When the reaction was carried out in the presence of a highly sterically demanding ligand (tri-*o*-biphenyl phosphite, TOPP),[16] the yield of **3a** did not improve (entry 15). A couple of bidentate ligands were also tested but the results were negative (entries 16 and

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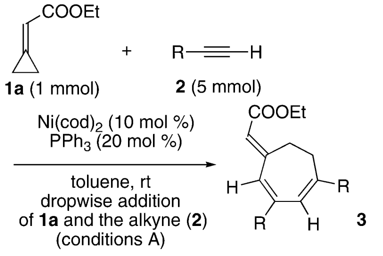
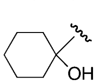
[16] TOPP was an efficient ligand for the nickel-catalyzed [4 + 3] cycloaddition of **1a** and 1,3-dienes. See ref 14c.

**TABLE 2. Nickel Catalyzed [3 + 2 + 2] Cocyclization of 1a and Terminal Alkynes (2)**



| entry | compound | R | yield of **3** (%) |
|---|---|---|---|
| 1 | **2a** | $(CH_3)_3Si$ | 70 |
| 2 | **2b** | $(CH_3)_3C$ | 89 |
| 3 | **2c** | $HO(CH_3)_2C$ | 56 |
| 4 | **2d** |  | 53 |
| 5 | **2e** | $BnMe_2Si$ | 47 |
| 6 | **2f** | Ph | 74 |
| 7 | **2g** | 4-$MeOC_6H_4$ | 72 |
| 8 | **2h** | 4-$FC_6H_4$ | 59[a] |
| 9 | **2i** | EtOOC | *b* |
| 10 | **2j** | *n*-$C_6H_{13}$ | *b* |

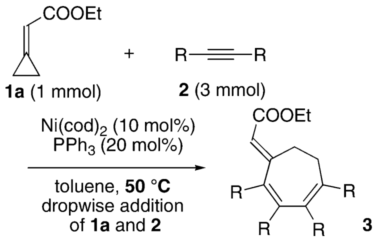
[a] The formation of a small amount of isomers was observed. [b] An inseparable mixture of cycloheptadiene derivatives, along with benzene derivatives, was isolated.

17). The reaction did not proceed in the absence of the phosphine ligand (entry 18). On the basis of these results, we selected $Ni(cod)_2-2PPh_3$ as the best catalyst for this reaction.

We also examined the reaction conditions and solvent effect on the yield of **3a**. The reaction proceeded smoothly and **3a** was isolated in good yield when the reaction was carried out in toluene and a solution of **1a** and **2a** (5 equiv) was added for 5 h (entry 1). On the other hand, the yield of **3a** decreased when a smaller amount of **2a** (3 equiv) was used (entry 19). The relationship between the addition time of a solution of the starting materials and the yield of **3a** was also examined. When a solution of **1a** and **2a** was added over a longer period (10 h) or at once, the yield of **3a** decreased (entries 20 and 22). On the other hand, the yield of **3a** did not decrease when a solution of **1a** and **2a** was added within 3 h (entry 21). The reaction was performed in various solvents, and acetonitrile and THF turned out to be good solvents for this reaction (entries 23 and 24). The yield of **3a** decreased when the reaction was carried out in ether or $CH_2Cl_2$ (entries 25 and 26). Though the reaction proceeded smoothly in dipolar aprotic solvents such as DMF or DMSO, the formation of inseparable isomers was observed (entries 27 and 28).

**[3 + 2 + 2] Cocyclization of Ethyl Cyclopropylideneacetate and Terminal Alkynes.** The reactions of **1a** with a series of terminal alkynes (**2**) were examined and the results are summarized in Table 2. The reaction proceeded in a highly selective manner and the cycloheptadienes (**3**) were isolated when bulky terminal alkynes were used. For example, the reaction of **1a** with 3,3-dimethyl-1-butyne (**2b**) proceeded smoothly and the product (**3b**) was isolated in 89% yield (entry 2). The yields of the corresponding cycloheptadienes were moderate when bulky propargyl alcohols such as **2c**,**d** were used as the substrates (entries 3 and 4). Though the reaction of benzyl(ethynyl)dimethylsilane (**2e**) with **1a** proceeded, the yield of the product was low (entry 5).

**TABLE 3. Nickel-Catalyzed [3 + 2 + 2] Cocyclization of 1a and Internal Alkynes (2n−r)**[a]



| entry | compd | R | yield of **3** (%) |
|---|---|---|---|
| 1 | **2n** | COOEt | 71 |
| 2 | **2o** | COOMe | 66 |
| 3 | **2p** | Ph | 39 |
| 4 | **2q** | *n*-$C_3H_7$ | 21[b] |
| 5 | **2r** | *n*-$C_6H_{13}$ | 23[b] |

[a] To a mixture of the Ni catalyst and **2** in toluene was added dropwise a solution of **1a** in toluene for 5 h. [b] The formation of a small amount of an isomer was observed.

We also found that arylacetylenes were good substrates for this reaction. The reaction of **1a** with phenylacetylene (**2f**) gave the corresponding cycloadduct (**3f**) in 74% yield (entry 6). The substituent effects on the reaction were examined and the result of the reaction of 4-methoxyphenylacetylene (**2g**) was comparable to that of **2f** (entry 7). Fortunately, the product **3g** gave a good single crystal, and the result of an X-ray crystallographic analysis[17] is illustrated in Figure S1 in the Supporting Information. It is noteworthy that the $\pi$ systems of the cycloheptadiene and exomethylene moiety are nearly coplanar. A small dihedral angle within the aliphatic $-CH_2CH_2-$ moiety of the cycloheptadiene ring was observed, indicating the existence of torsional strain.

The formation of an isomeric cycloheptadiene was observed when an electron-withdrawing group was introduced to the aromatic ring (entry 8). The selectivity of the reaction was lost and the formation of isomers was observed when the reaction of **1a** with ethyl propiolate (**2i**) or 1-octyne (**2j**) was carried out (entries 9 and 10). Though none of the isomeric compounds from these reactions could be isolated, isolation of the isomers was successful when the reaction of **1a** was carried out with 4-(trifluoromethyl)phenylacetylene (**2k**), *n*-perfluorooctylacetylene (**2*l***), or propargyl alcohol (**2m**). Thus, compound **3k** and a small amount of **4** were isolated in the reaction of **2k** (eq 1). The result indicates that the selectivity of the reaction was controlled by the electronic factor as well as the steric factor. The importance of the substituent effects on the selectivity was further demonstrated by the reaction of a highly fluorinated alkyne. Thus, the reaction of **1a** with *n*-perfluorooctylacetylene (**2*l***) gave the cycloheptadiene **5** as a single isomer in 60% yield (eq 2). On the other hand, the reaction of **1a** with **2m** gave **6**, together with a small amount of **3m** (eq 3). The result may indicate the reduced selectivity and the higher reactivity of the

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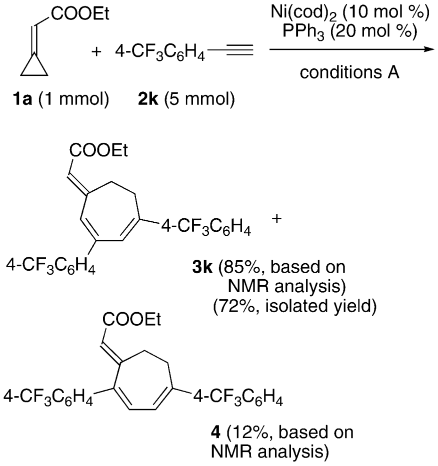
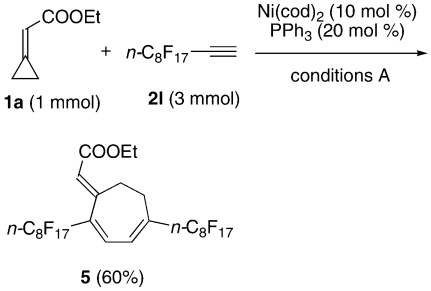
(17) See the Supporting Information for the details.



(1)



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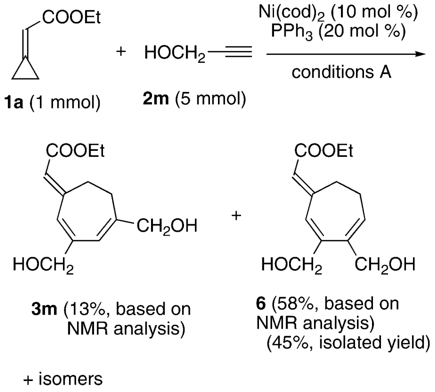
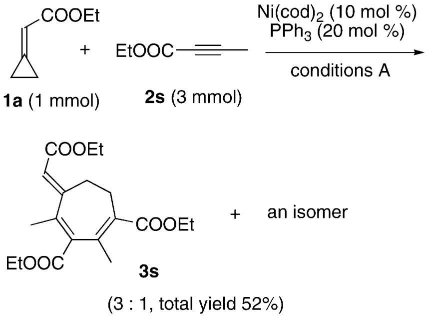


(3)

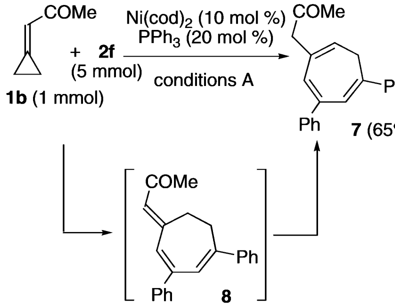
corresponding nickelacyclopentadiene intermediate (vide infra). We assume that similar isomers were formed in the reaction of alkynes **2i**,**j**.

**[3 + 2 + 2] Cocyclization of Ethyl Cyclopropylideneacetate (1a) and Internal Alkynes.** The results of the reactions of **1a** with a series of internal alkynes (**2n**−**r**) are summarized in Table 3. Compared to terminal alkynes, the reactivity of the internal alkynes was generally low. The products were isolated in best yields when the reaction was carried out at 50 °C and 3 equiv of the alkyne was employed. The reaction of **1a** with diethyl acetylenedicarboxylate (**2n**), as well as dimethyl acetylenedicarboxylate (**2o**), gave the cycloheptadiene derivatives in good yields (entries 1 and 2). On the other hand, the yields of the products decreased when other alkynes such as diphenylacetylene (**2p**), 4-octyne (**2q**), or 7-tetradecyne (**2r**) were used (entries 3−5). The [3 + 2 + 2] cocyclization of unsymmetric internal alkynes such as ethyl but-2-ynoate (**2s**) gave a mixture of the isomeric cycloheptadienes (eq 4). The major isomer (**3s**) was isolated, and the structure was determined by NOESY experiments. The reactions of internal alkynes with a bulky substituent (e.g., 1-trimethylsilyl-1-octyne) did not proceed.



(4)

**[3 + 2 + 2] Cocyclization of 1-Cyclopropylidene-2-propanone (1b) and Alkynes.** To examine the scope of the [3 + 2 + 2] cocyclization, the reactions of 1-cyclopropylidene-2-propanone **(1b)** with alkynes were examined. The results are shown in eqs 5−7. The [3 + 2 + 2] cocyclization of **1b** with phenylacetylene (**2f**) proceeded well, and compound **7** was isolated in 65% yield (eq 5). It is assumed that the product **7** was formed by a rapid isomerization of the corresponding cycloheptadiene **8**, which would be formed as the initial product. A more complicated result was obtained when the reaction of



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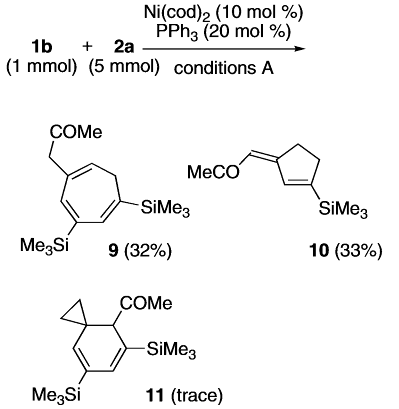

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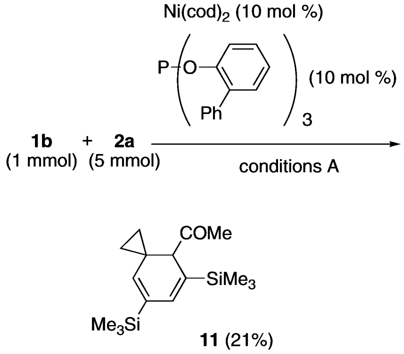
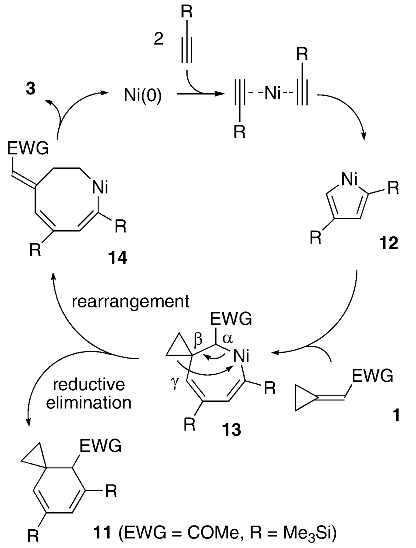


(7)

**SCHEME 1**



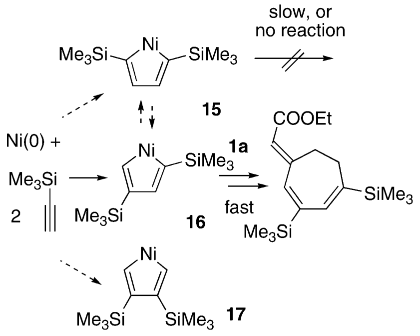
**1b** with trimethylsilylacetylene (**2a**) was carried out. Thus, the formation of a [3 + 2] cycloadduct **10** and a trace amount of a [2 + 2 + 2] cycloadduct **11**, along with the expected [3 + 2 + 2] cycloadduct **9**, was observed (eq 6). Compound **11** was isolated in 21% yield when the reaction was carried out in the presence of Ni(cod)$_2$−TOPP (tri-*o*-biphenylyl phosphite) (eq 7).[16,18] The formation of **11** as a product in these reactions suggests that the reaction proceeds via the insertion of the C=C double bond of the methylenecyclopropane to the nickelacycle (vide infra).

**Mechanistic Consideration of the [3 + 2 + 2] Cocyclization.** The selective formation of seven-membered carbocycles in many examples is the most interesting feature of the reaction. On the basis of the results of the reactions and the observed isomeric byproducts, a possible catalytic pathway is outlined in Scheme 1 (phosphine ligands are omitted for clarity). The formation and reaction of the nickelacyclopentadiene and the ring expansion reaction would be the characteristics of the reaction.

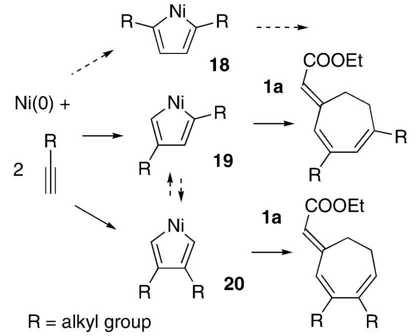
The reaction is initiated by the interaction of the Ni(0)−PPh$_3$ complex, which is generated by the reaction of Ni(cod)$_2$ and PPh$_3$, with alkynes. The Ni−alkyne $\pi$ complex further reacts to give the nickelacyclopentadiene **12**, which is postulated as an intermediate for various catalytic reactions.[7,19] The ratio and the reactivity of the complex would play an important role for the overall selectivity. The results of the reaction of various alkynes indicated that the selectivity of the reaction was controlled by the steric factors as well as the electronic factors of the substituents.

When terminal alkynes react with the Ni(0) complex, three possible isomeric nickelacyclopentadienes may be postulated as the intermediates (Schemes 2−4, phosphine ligands are omitted for clarity). The ratio and the reactivity of the isomers are controlled by the steric as well as electronic nature of the substituents. When trimethylsilylacetylene (**2a**) was selected as the alkyne, the selective formation of **3a** was observed. The result indicated that the reaction of the Ni(0) species with **2a** gives **16** selectively, and/or the reactivity of **16** is higher compared to that of other isomers (Scheme 2). On the basis of the analysis of the $\pi^*$ orbital of **2a**, the most stable isomer would be **15**.[20] In fact, Ikeda and co-workers proposed that a Ni complex similar to **15** is a reactive intermediate of the [2 + 2 + 2] cocyclization of enone with alkynes.[19a] However, they also mentioned that an intermediate similar to **16** is a kinetically favored product, based on the observed relationship between the reaction time and isomer ratio of the products. The formation of **16** would be kinetically favored because the antiparallel alignment of **2a** is more stable due to the steric reason. Furthermore, the reactivity of **16** must be higher because one of the Ni−C bonds is less sterically congested. Compound **1a** is a sterically congested alkene, and it is assumed that **1a** reacts selectively with the less sterically congested Ni−C bond, as indicated in Schemes 1 and 2. On the other hand, the reaction

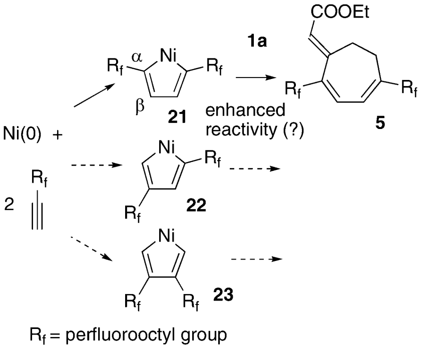
**SCHEME 2**



**SCHEME 3**



**SCHEME 4**



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[18] A similar spiro compound was isolated in the reaction of **1a** with 1,3-dienes. See ref 14c.

[19] Examples: (a) Mori, N.; Ikeda, S.-i.; Sato, Y. *J. Am. Chem. Soc.* **1999**, *121*, 2722−2727. (b) Chalk, A. J. *J. Am. Chem. Soc.* **1972**, *94*, 5928−5929. (c) Heimbach, P.; Ploner, K. J.; Thoemel, F. *Angew. Chem., Int. Ed. Engl.* **1971**, *10*, 276−277. (d) Balaich, G. J.; Rothwell, I. P. *J. Am. Chem. Soc.* **1993**, *115*, 1581−1583. (e) Ikeda, S.-i.; Mori, N.; Sato, Y. *J. Am. Chem. Soc.* **1997**, *119*, 4779−4780.

[20] Stockis, A.; Hoffmann, R. *J. Am. Chem. Soc.* **1980**, *102*, 2952−2962.

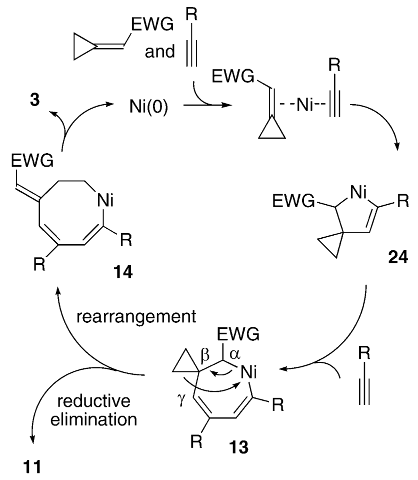
of Ni(0) species with less sterically congested alkynes usually gives a mixture of nickelacyclopentadienes, which have similar reactivities. Consequently, a mixture of isomeric products was generally isolated (Scheme 3). Though we could not separate the isomers in most reactions, we assume that the isomer distributions would be similar to those observed in the reaction of propargyl alcohol (eq 3). The observed selectivity of the product would be explained in terms of the formation of **19** and **20** as the intermediates. Considering the electronic factor, the formation of **20** would be favored. The concomitant formation of **19** could be explained in terms of the steric repulsion between the substituents.

The result of the reaction of **1a** with perfluorooctylacetylene (**2*l***) was exceptional, and the result indicated that both substituents occupied the $\alpha$ position of the nickelacyclopentadiene intermediate (Scheme 4). The analysis of the $\pi^*$ MO indicated that the intermediate **21** would be thermodynamically stable.[20,21] It is assumed that the intermediate **21** is also a kinetically favored intermediate because the parallel alignment of **2*l*** is more stable due to the smaller steric interaction between the two perfluorooctyl groups. The isomer **21** was formed predominantly and further reacts with **1a**. The reactivity of **21** might be enhanced by the introduction of a perfluoroalkyl group.

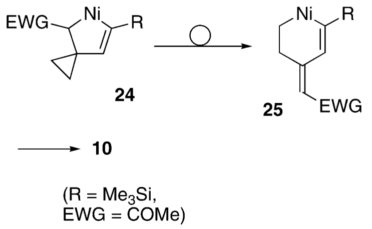
The next step of the reaction is the insertion of **1** into the nickelacyclopentadiene. It is assumed that this insertion of **1** occurs into the less sterically encumbered Ni−C bond. Though the possibility of the direct insertion of the strained C−C $\sigma$ bond of **1** into the Ni−C bond of the metallacycle cannot completely be excluded,[22] it is more likely that the insertion of the C═C double bond into the Ni−C bond occurred. The selective insertion of **1a**, instead of **2a**, to **13** is controlled by the slow addition of the substrates to the solution of the catalyst: the concentration of the uncoordinated alkyne was kept low (Scheme 1). Considering the polarity of the Ni−C bond, the anionic carbon atom would be connected to the electrophilic carbon atom of the enoate. The isolation of the six-membered spiro compound **11** in the reaction of **1b** with **2a** in the presence of TOPP provides indirect evidence for the formation of the seven-membered metallacycle **13**: the reductive elimination of the Ni(0) species from **13** would provide **11**, whereas the cyclopropylmethyl to butenyl rearrangement[23,24] of **13** followed by the reductive elimination of a Ni(0) species would give the cycloheptadiene **3** (Scheme 1). The bulky TOPP ligand would accelerate the reductive elimination and the spiro compound **11** would be generated preferentially. In the rearrangement of **13**, the *s-trans* conformation of the C(EWG)−C($\alpha$)−C($\beta$)−C($\gamma$) bond would be preferred, and as a result the *E* isomer would be formed selectively (Scheme 1).

In the reaction of **1b** with **2a**, the formation of the cyclopentene **10** was observed (eq 5). Unlike other reactions, this one might proceed via the formation of a nickelacyclopentene by the reaction of **1b**, **2a**, and the Ni(0) species. The higher reactivity of **1b** compared to **1a** might induce the formation of the nickelacyclopentene. Alternatively, the insertion of the Ni(0) species to the strained C−C single bond of the reactive **1b** and the insertion of **2a** might take place.[4c,12]

**SCHEME 5**



An alternative mechanism of this reaction is shown in Scheme 5. Thus, the formation of a nickelacyclopentene (**24**) may proceed, the insertion of the second alkyne follows, and compound **13** is formed. The mechanism shown in Scheme 5 is less likely, because the rearrangement of **24** should occur easily to give **25**, and the cyclopentene derivative such as **10** would be isolated as the major product (eq 8). In fact, a series of [3 + 2] cycloaddition reactions is reported in the literature.[2h,i,13] If the nickelacyclopentene (**24**) is formed by the reaction of **1a** with trimethylsilylacetylene (**2a**), the insertion of **2a** to the nickelacyclopentene would be very slow (or completely inhibited) because of the large steric hindrance of the trimethylsilyl group. Furthermore, it is quite difficult to explain the formation of **5** by the reaction of **1a** with perfluorooctylacetylene (**2*l***, eq 2). In this reaction, the nickelacyclopentene **26** (not **28**) would be the predominant intermediate because of the electronic effect of the substituent. The observed product was **5**, which would not be generated by the reaction of **26** with the alkyne (Scheme 6).[25] On the other hand, the observed selectivity of the reaction of **2*l*** could be easily explained by the mechanism postulated in Scheme 1 and the consideration of the structure of the nickelacyclopentadiene intermediate (Scheme 4).



(8)

## Summary

The intermolecular [3 + 2 + 2] cocyclization of ethyl cyclopropylideneacetate and various alkynes was developed. On the basis of the results of the reactions and the observed byproducts, the mechanism and the selectivity of the reaction

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[21] Marakchi, K.; Kabbaj, O. K.; Komiha, N. *J. Fluorine Chem.* **2002**, *114*, 81−89.

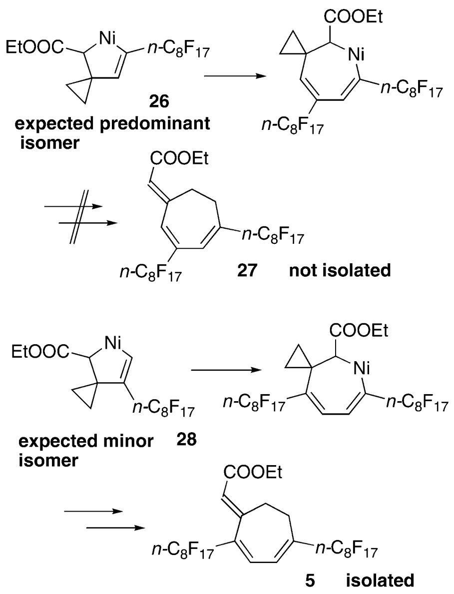
[22] (a) Neidlein, R.; Rufinska, A.; Schwager, H.; Wilke, G. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 640−642. (b) Mynott, R.; Neidlein, R.; Schwager, H.; Wilke, G. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 367−368. (c) Krüger, C.; Laakmann, K.; Schroth, G.; Schwager, H.; Wilke, G. *Chem. Ber.* **1987**, *120*, 471−475. (d) Schwager, H.; Spyroudis, S.; Vollhardt, K. P. C. *J. Organomet. Chem.* **1990**, *382*, 191−200.

[23] Binger, P.; Doyle, M. J.; Benn, R. *Chem. Ber.* **1983**, *116*, 1−10.

[24] A reaction that involves a similar rearrangement has been recently reported. See: Murakami, M.; Ashida, S.; Matsuda, T. *J. Am. Chem. Soc.* **2006**, *128*, 2166−2167.

[25] It is also difficult to explain the formation of the isomer in the reaction of **1a** with **2k** (eq 1).

**SCHEME 6**



can be discussed. The study highlights the importance of the substituent effect on the nickel-catalyzed cycloaddition reactions of unsaturated hydrocarbons.

Compared to the rich chemistry of the cycloaddition reactions available for the synthesis of six-membered carbocycles, fewer cycloaddition reactions are available for the synthesis of seven-membered carbocycles. The current study provides a new and efficient method for the synthesis of seven-membered carbocycles. The application of this method to the synthesis of various cycloheptane derivatives is currently underway.

## Experimental Section

**Nickel(0)-Catalyzed Cocyclization of Ethyl Cyclopropylideneacetate (1a) and Alkynes: A Representative Procedure.** To a dark red mixture of Ni(cod)$_2$ (27.5 mg, 0.1 mmol) and PPh$_3$ (52.5 mg, 0.2 mmol) in anhydrous toluene (0.5 mL) was added dropwise a solution of **1a** (124 mg, 0.98 mmol) and **2** (5 mmol) in anhydrous toluene (0.5 mL) at room temperature within 5 h under Ar. The progress of the reaction was monitored by TLC and GC-MS, and the mixture was stirred until the starting material **1a** had disappeared (overnight). The mixture was passed through a short silica gel (or alumina) column eluting with ether. Evaporation of the solvent gave an oil, which was further purified by silica gel column chromatography to give **3**.

**(*E*)-1-Ethoxycarbonylmethylene-3,5-bis(trimethylsilyl)-2,4-cycloheptadiene (3a).** The product was purified by silica gel column chromatography (hexane/AcOEt 20:1): 222 mg (70% yield); yellow oil; $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 6.44 (s, 1H), 6.29 (s, 1H), 5.65 (s, 1H), 4.13 (q, $J = 7.1$ Hz, 2H), 3.07−3.02 (m, 2H), 2.29−2.25 (m, 2H), 1.25 (t, $J = 7.1$ Hz, 3H), 0.12 (s, 9H), 0.09 (s, 9H); $^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 167.1, 159.4, 151.1, 147.8, 141.1, 135.1, 117.0, 59.7, 32.0, 27.8, 14.3, −1.7, −2.2; IR (neat) 3896, 3782, 3734, 2954, 2900, 1705, 1597, 1442, 1404, 1257, 1211, 1157, 1087, 1041, 833, 748, 694 cm$^{-1}$. HR-MS calcd for $C_{17}H_{30}O_2Si_2$ 322.1785, found 322.1771.

**Acknowledgment.** The authors thank Tokyo University of Science (Special Grants), Mitsubishi Chemical Corporation Fund, Saneyoshi Scholarship Foundation, and The Kurata Memorial Hitachi Science and Technology Foundation for financial support.

**Supporting Information Available:** Figure S1 giving detailed experimental procedures (pdf) and details of X-ray structure determination of **3g** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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