Preparation of Diynes via Selective Bisalkynylation of Zirconacycles

Yuanhong Liu, Chanjuan Xi, Ryuichiro Hara, Kiyohiko Nakajima,† Akiko Yamazaki, Martin Kotora, and Tamotsu Takahashi*

Catalysis Research Center and Graduate School of Pharmaceutical Sciences, Hokkaido University, Kita-ku, Sapporo 060-0811, Japan, CREST, Science and Technology Corporation (JST), Sapporo 060-0811, Japan, and Department of Chemistry, Aichi University of Education, Igaya, Kariya, Aichi 448-8542, Japan

tamotsu@cat.hokudai.ac.jp

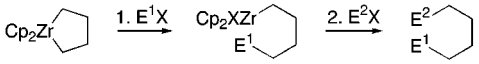
Received April 11, 2000

Reaction of alkynyl halides with in situ prepared zirconacyclopentanes, -pentenes, and -pentadienes in the presence of CuCl under mild reaction conditions afforded alkynes or diynes. Control of the reaction conditions selectively afforded monoalkynylation products of zirconacycles. Reaction of zirconacycles with 2 equiv of alkynyl halides resulted in the formation of diynes. Selective monoalkynylation of zirconacycle with an alkynyl halide, followed by reaction with a different alkynyl halide, afforded unsymmetrical diynes. Bisalkynylation product of zirconacyclopentadiene was gradually converted into a tricyclic compound.

Introduction

Selective transformation of metallacycles can provide powerful methods for the construction of bisfunctionalized molecules in one pot from simple starting materials such as alkenes and alkynes.[1] As a typical example may serve recent advances in transformations of zirconacycles in which two Zr−C bonds showed various reactions.[2] A special feature of the zirconacycles is the considerably different reactivity of the two Zr−C bonds in a zirconacycle (in the case of zirconacyclopentanes, -cyclopentenes, and -pentadienes) in comparison with the Zr−C of open-chained organozirconium compounds. This difference has enabled us to develop a number of methods for selective sequential functionalization of zirconacycles with two different electrophiles with high chemo- and regioselectivity. Such methodologies include bisfunctionalization of zirconacyclopentane (acylation−iodination,[3a] selective acylation and allylation[3b]), zirconacyclopentene (chemoselective halogenation and stannylation,[4a−c] regioselective allylation,[4d,5] Michael reaction[6]), and zirconacyclopentadiene (dihalogenation,[7a] diallylation,[7b] dibenzylation[7c]). Also, we have recently found that alkenyl- and dienylzirconium compounds could easily react with alkynyl halides in the presence of a stoichiometric amount of CuCl to give highly substituted enynes[8] or dieneynes[9] in good yields (Scheme 1).

Scheme 1



Thus, we envisioned that the selective bisalkynylation with a 2-fold excess of alkynyl halide or the selective sequential alkynylation with two different alkynyl halides would afford diynes.[10] Accordingly, the combination of two alkenes and two alkynyl halides would give diynes, the combination of an alkyne and an alkene would result in the formation of enediynes, and finally the combination of two alkynes and two alkynyl halides would afford

† Aichi University of Education.

(1) (a) Lautens, M.; Klute, W.; Tam, W. *Chem. Rev.* **1996**, *96*, 49−92. (b) *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Elsevier Science Ltd.: Oxford, 1995; Vol 12. (c) *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds; Pergamon Press Ltd.: Oxford, 1991; Vol. 5. (f) Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 539−556.

(2) (a) Kotora, M.; Xi, Z.; Takahashi, T. *J. Synth. Org. Chem.* **1997**, *55*, 36−47. (b) Takahashi, T.; Xi, Z.; Kotora, M. *Recent Res. Dev. Pure Appl. Chem.* **1998**, *2*, 515−525. (c) Negishi, E.; Swanson, D. R.; Miller, S. R. *Tetrahedron Lett.* **1988**, *29*, 1631−1634. (d) Dekura, F.; Honda, T.; Mori, M. *Chem. Lett.* **1997**, 825. (e) Fillery, S. F.; Gordon, G. J.; Luker, T.; Whitby, R. J. *Pure Appl. Chem.* **1997**, *69*, 633−638.

(3) For copper-mediated C−C bond formation: see: (a) Takahashi, T.; Kotora, M.; Xi, Z. *J. Chem. Soc., Chem. Commun.* **1995**, 1503−1504. (b) Takahashi, T.; Nishihara, Y.; Hara, R.; Huo, S.; Kotora, M. *Chem. Commun.* **1997**, 1599−1600. (c) Lipshutz, B. H.; Ellsworth, E. L. *J. Am. Chem. Soc.* **1990**, *112*, 7440−7441. (d) Babiak, K. A.; Behling, J. R.; Dygos, J. H.; McLanghlin, K. T.; Ng. J. S.; Kalish, V. J.; Kramer, S. W.; Shone, R. L. *J. Am. Chem. Soc.* **1990**, *112*, 7441−7442. (e) Lipshutz, B. H.; Hato, K. *Tetrahedron Lett.* **1991**, *32*, 5647−5650. (f) Lipshutz, B. H.; Fatheree, P.; Hagan, W.; Stevens, K. L. *Tetrahedron Lett.* **1992**, *33*, 1041−1044. (g) Lipshutz, B. H.; Keil, R. *J. Am. Chem. Soc.* **1992**, *114*, 7919−7920. (h) Lipshutz, B. H.; Wood, M. R. *J. Am. Chem. Soc.* **1993**, *115*, 12625−12626.

(4) (a) Takahashi, T.; Aoyagi, K.; Hara, R.; Suzuki, N. *J. Chem. Soc., Chem. Commun.* **1993**, 1042−1044. (b) Takahashi, T.; Aoyagi, K.; Kondakov, D. Y. *J. Chem. Soc., Chem. Commun.* **1994**, 747−748. (c) Aoyagi, K.; Kasai, K.; Kondakov, D. Y.; Hara, R.; Suzuki, N.; Takahashi, T. *Inorg. Chim. Acta* **1994**, *220*, 319−326. (d) Kasai, K.; Kotora, M.; Suzuki, N.; Takahashi, T. *J. Chem. Soc., Chem. Commun.* **1995**, 109−110.

(5) For the selective reaction at the Zr−sp^2C bond, see also: Honda, T.; Mori, M. *Organometallics* **1996**, *15*, 5464−5466.

(6) Lipshutz, B. H.; Segi, M. *Tetrahedron* **1995**, *51*, 4407−4420.

(7) (a) Ubayama, H.; Xi, Z.; Takahashi, T. *Chem. Lett.* **1998**, 517−518. (b) Takahashi, T.; Kotora, M.; Kasai, K.; Suzuki, N.; Nakajima, K. *Organometallics* **1994**, *13*, 4183−4185. (c) Takahashi, T.; Sun, W.-H.; Liu, Y.; Nakajima, K.; Kotora, M. *Organometallics* **1998**, *17*, 3841−3843.

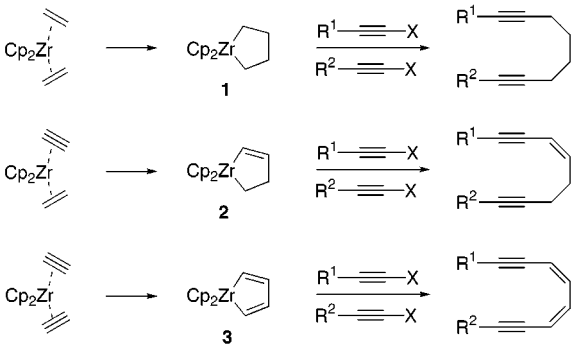
(8) Hara, R.; Liu, Y.; Sun, W.-H., Takahashi, T. *Tetrahedron Lett.* **1997**, *38*, 4103−4106.

(9) Takahashi, T.; Sun, W.-H.; Xi, C.; Ubayama, H.; Xi, Z. *Tetrahedron* **1998**, *54*, 715−726.

(10) For the coupling reaction between alkynyl halide and organometallic reagent, see: (a) Oliver, R.; Walton, D. R. M. *Tetrahedron Lett.* **1972**, *51*, 5209−5212. (b) Commerçon, A.; Normant, J. F.; Villieras, J. *Tetrahedron* **1980**, *36*, 1215−1221. (c) Yeh, M. C. P.; Knochel, P. *Tetrahedron Lett.* **1989**, *30*, 4799−4802. (d) Sörensen, H.; Greene, A. E. *Tetrahedron Lett.* **1990**, *31*, 7597−7598. (e) Knoess, H. P.; Furlong, M. T.; Rozema, M. J.; Knochel, P. *J. Org. Chem.* **1991**, *56*, 5974−5978. (f) Micouin, L.; Oestreich, M.; Knochel, P. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 245−246.

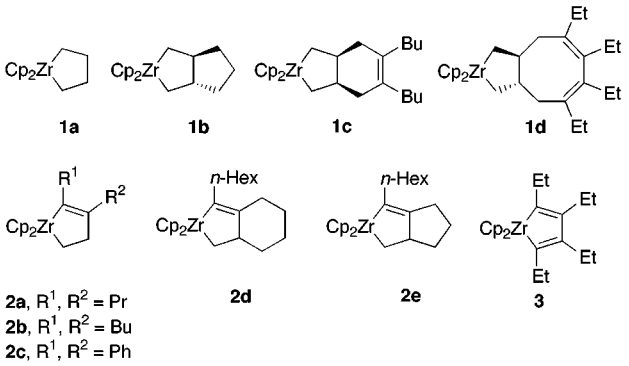
10.1021/jo0005417 CCC: $19.00
Published on Web 09/19/2000

Scheme 2



dienediynes (Scheme 2). The overall process was designed as a one-pot reaction sequence that starts from the zirconium-mediated transformation of such simple starting material as alkenes and alkynes.

To establish the scope of mono- and bisalkynylation, a number of various zirconocycles such as zirconacyclopentanes **1a**−**d**,[11] -pentenes **2a**−**e**,[12] and -pentadiene **3**[13] were used. In all cases, the zirconacycles were prepared prior to the reaction in situ from the corresponding alkenes, dienes, enynes, or alkynes.

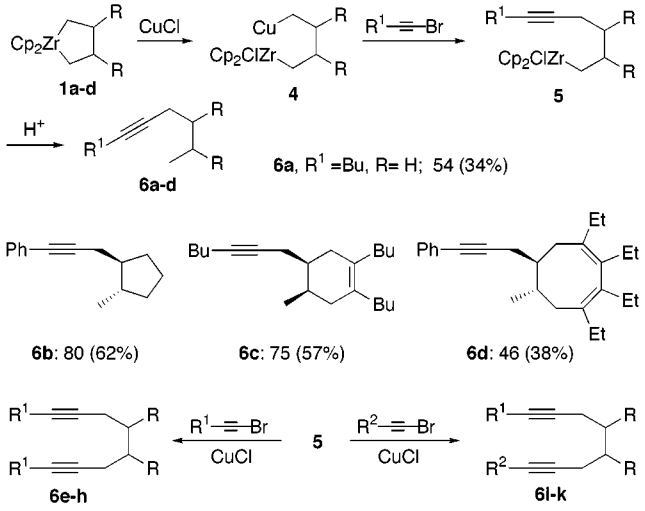


2a, R^1, R^2 = Pr
2b, R^1, R^2 = Bu
2c, R^1, R^2 = Ph

Results and Discussion

Bisalkynylation of Zirconacyclopentanes. Our first target was to find reaction conditions under which selective monoalkynylation of zirconacyclopentanes would proceed. Development of the selective monoalkynylation was essential for the later development of unsymmetrical bisalkynylation (vide infra). In our plan we relied on the fact that it has been shown that CuCl may cleave only one Zr−C bond of zirconacyclopentane **1** to give **4**, which could selectively react with electrophiles.[3a,b] Indeed, we found that the selective monoalkynylation of zirconacyclopentanes proceeded efficiently with 1 equiv of an alkynyl halide in the presence of CuCl at ambient temperature to give the corresponding products after hydrolysis of the reaction mixture with with 3 N HCl (Scheme 3). It is reasonably assumed that intermediate

Scheme 3



4 reacted with an alkynyl halide to give **5**, which after hydrolysis afforded the products **6**.

Monoalkynylation of simple zirconacyclopentane **1a** with 1-hexynyl bromide proceeded in the presence of a stoichiometric amount (1 equiv) of CuCl and afforded 5-decyne **6a**. Monoalkynylation of bicyclic zirconacyclopentanes **1b**−**c** proceeded with a catalytic amount of CuCl and provided the corresponding alkynylated derivatives **6b**−**d** with five and six rings in good yields. CuCl is changed to CuBr after the reaction with alkynyl bromide. The CuBr is not so reactive toward the transmetalation of monocyclic zirconacyclopentanes. Therefore, a stoichiometric amount of CuCl is needed. In contrast, bicyclic zirconacyclopentanes are very reactive. Even CuBr can effect the transmetalation reaction of bicyclic zirconacyclopentanes. Therefore, the first alkynylation of bicyclic zirconacyclopentanes can be catalytic. In contrast to **1b**−**c**, monoalkynylation of **1d** had to be carried out at 0 °C in the presence of 1 equiv of CuCl to obtain at least a moderate yield of the monoalkynylated product **6d**. It is important to note that transmetalation of the Zr−C bond in **5** to the Cu−C bond[3] results in facile cyclization that leads to exocyclic olefin as we reported.[14] To avoid such cyclization, only 1 equiv or a catalytic amount of CuCl should be used.

Symmetrical bisalkynylation of zirconacyclopentanes proceeded with 2 equiv of alkynyl halide in the presence of 2 equiv of CuCl at room temperature. Some representative examples are given in Table 1. The reaction mechanism was similar, and intermediate **5** reacted after transmetalation with CuCl with the second equivalent of alkynyl halide to give diynes **6e**−**h**. In the presence of an alkynyl halide, the coupling of **5** with alkynyl halide was much faster than intramolecular cyclization. Bisalkynylation of zirconacyclopentane **1a** with 2 equiv of hexynyl bromide afforded diyne **6e** in a rather moderate yield. On the other hand, bicyclic zirconacyclopentanes **1b**−**d** reacted with alkynyl halides very fast to give the corresponding diynes **6f**−**h** in good yields.

The successful development of the selective monoalkynylation of zirconacycles outlined the feasibility of unsymmetrical bisalkynylation with two different alkynyl halides. Thus, the initial reaction of a zirconacycle with

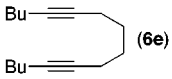
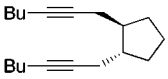
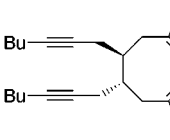
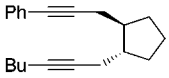
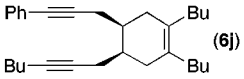
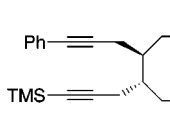
(11) (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829−2832. (b) Rousset, C. J.; Swanson, D. R.; Lamaty, F.; Negishi, E. *Tetrahedron Lett.* **1989**, *30*, 5105−5108.

(12) (a) Negishi, E.; Holmes, S. E.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3089−3091. (b) Takahashi, T.; Xi, Z.; Rousset, C. J.; Suzuki, N. *Chem. Lett.* **1993**, 1001−1003. (c) Takahashi, T.; Kageyama, M.; Denisov, V.; Hara, R.; Negishi, E. *Tetrahedron Lett.* **1993**, *34*, 687−690. (d) Xi, Z.; Hara, R.; Takahashi, T. *J. Org. Chem.* **1995**, *60*, 4444−4448 and references therein.

(13) (a) For symmetrically substituted ones, see ref 11a. (b) For unsymmetrically substituted ones, see ref 12d.

(14) Liu, Y.; Shen, B. Kotora, M.; Takahashi, T. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 949−952.

Table 1. Bisalkynylation of Zirconacyclopentanes 1

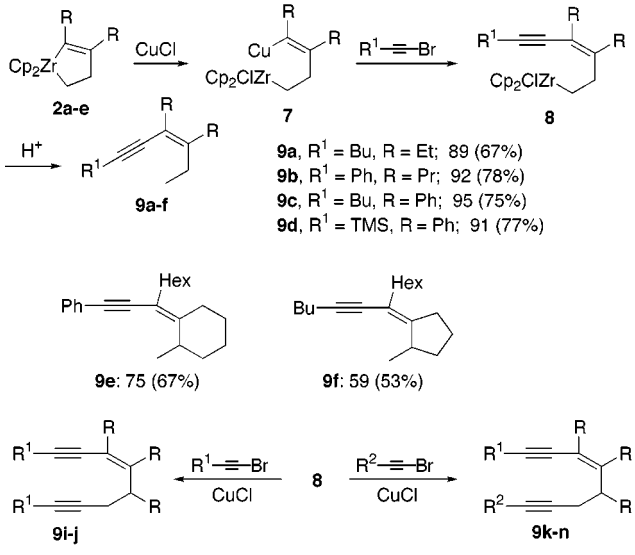
Zirconacycle	Alkynyl bromide	Conditions	Products	Yield(%)[a]
1a	Bu—≡—Br	20°C, 6h	 **(6e)**	45 (36)
1b	Bu—≡—Br	20°C, 1h	 **(6f)**	66 (53)
1b	Hex—≡—Cl	20°C, 1h	 **(6g)**	58 (47)
1d	Bu—≡—Br	20°C, 1h	 **(6h)**	84 (69)
1b	Ph—≡—Br Bu—≡—Br	0°C, 1h 20°C, 12h	 **(6i)**	61 (56)
1c	Ph—≡—Br Hex—≡—Br	0°C, 1h 20°C, 12h	 **(6j)**	60 (53)
1d	Ph—≡—Br TMS—≡—Br	0°C, 3h 20°C, 3h	 **(6k)**	- (28)

[a] GC yield. Isolated yield are given in parentheses.

1 equiv of an alkynyl halide in the presence of CuCl, under the conditions required for the monoalkynylation (see the formation of **6b**−**d**), cleaved one of the two Zr−C bonds and afforded the monoalkynylated intermediate **5** with one Zr−C bond. After addition of 1 equiv of a different alkynyl halide and additional 1 equiv of CuCl, the remaining Zr−C bond reacted (after transmetalation with Cu salts present in the reaction mixture) to give unsymmetrically bisalkynylated products **6i**−**k**. Typical examples are given in Table 1. Thus, initial monoalkynylation of bicyclic zirconacyclopentanes **1b,c** with phenylethynyl bromide in the presence of a catalytic amount of CuCl at 0 °C for 1 h followed by the reaction with hexynyl bromide and an additional 1 equiv of CuCl at 20 °C for 12 h afforded the unsymmetrically alkynylated products **6i,j** in good yields. Sequential monoalkynylation of zirconacyclopentane **1d** with phenylethynyl bromide in the presence of 1 equiv of CuCl at 0 °C followed by the reaction with trimethylsilylethynyl bromide and additional 1 equiv of CuCl at 20 °C afforded a disappointingly low yield of **6k**.

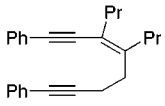
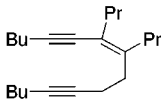
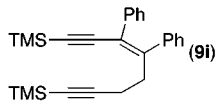
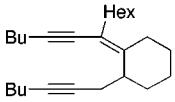
Bisalkynylation of Zirconacyclopentenes. Monoalkynylaton of zirconacyclopentenes proceeded in a similar fashion; however, a stoichiometric amount (1 equiv) of CuCl was required. The monoalkynylation proceeded selectively at the Zr−sp^2C bond, as was expected according to the previously published data,[4d] through intermediates **7** and **8** (Scheme 4). Hydrolysis of the reaction

Scheme 4



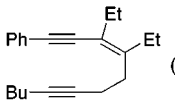
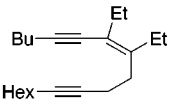
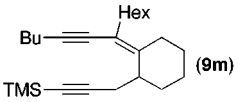
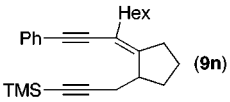
mixture furnished the corresponding substituted enynes **9a**−**f** (Table 2). Thus, monoalkynylation of monocyclic zirconacyclopentenes **2a**−**c** proceeded fast at room temperature and gave enynes **9a**−**d** in high yields. Monoalkynylation of bicyclic zirconacyclopentenes **2d,e** had to be carried out at 0 °C and gave cyclic enynes **9e,f** in good yields.

Table 2. Bisalkynylation of Zirconacyclopentenes 2

Zirconacycle	Alkynyl halide	Conditions	Products	Yield (%)[a]
2b	Ph—≡—Br	20°C, 9h[b]	 **(9g)**	- (53)
2b	Bu—≡—Br	20°C, 9h[c]	 **(9h)**	50 (40)
2c	TMS—≡—Br	20°C, 1h[c]	 **(9i)**	56 (52)
2d	Bu—≡—Br	20°C, 3h	 **(9j)**	84 (67)

[a] GC yield. Isolated yield are given in parentheses. [b] Then 50 °C, 6 h. [c] Then 50 °C, 3 h.

Table 3. Unsymmetrical Bisalkynylation of Zirconacyclopentenes 2

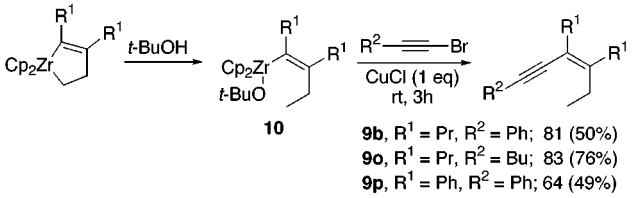
Zirconacycle	Alkynyl halides	Conditions	Product	Yield (%)[a]
2a	Ph—≡—Br Bu—≡—Br	20°C, 1h 50°C, 6h	 **(9k)**	46 (41)
2a	Bu—≡—Br Hex—≡—Br	20°C, 1h 50°C, 6h	 **(9l)**	40 (35)
2d	Bu—≡—Br TMS—≡—Br	0°C, 1h 0°C, 3h	 **(9m)**	52 (48)
2e	Ph—≡—Br TMS—≡—Br	0°C, 1h 0°C, 3h	 **(9n)**	73 (58)

[a] GC yield. Isolated yield are given in parentheses.

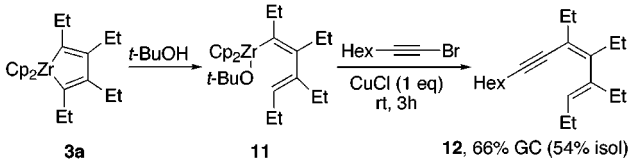
Generally, bisalkynylation of zirconacyclopentenes with 2 equiv of alkynyl halide required the presence of 2 equiv of CuCl and room temperature; however, in certain cases heating of the reaction mixture increased yields of the products (Table 2). In comparison to monoalkynylation, bisalkynylation of monocyclic zirconacyclopentenes **2b,c** required prolonged reaction time and higher reaction temperature (50 °C) to obtain the corresponding enediynes **9g**−**i** in reasonable yields. An especially sluggish step turned out to be the transmetalation and alkynylation of the remaining Zr−sp^3C bond in **8** (Scheme 4). On the other hand, bisalkynylation of bicyclic zirconacyclopentene **2d** proceeded uneventfully at room temperature with a high yield of enediyne **9j**.

Unsymmetrical alkynylation of zirconacyclopentenes with two different alkynyl halides was carried out similarly to bisalkynylation of zirconacyclopentanes; that is, zirconacyclopentene reacted at first with 1 equiv of alkynyl halide to give **8**, which reacted further with a different alkynyl halide to provide enediynes **9k**−**n** (Scheme 4). For representative examples see Table 3. The reaction of zirconacyclopentene **2a** with phenylethynyl bromide in the presence of 2 equiv of CuCl at room temperature, followed by the reaction with hexynyl bromide at 50 °C, afforded **9k** in moderate yield. The sequential reaction of **2a** with hexynyl bromide and octynyl bromide gave **9l** in a similar yield. On the other hand, reaction of bicyclic zirconacyclopentenes **2d** and **2e** with the first alkynyl halide in the presence of 2 equiv of CuCl proceeded at 0 °C for 1 h and was followed by the reaction with the second alkynyl halide at the same temperature for 3 h. Enediynes **9m** and **9n** were obtained in good yields.

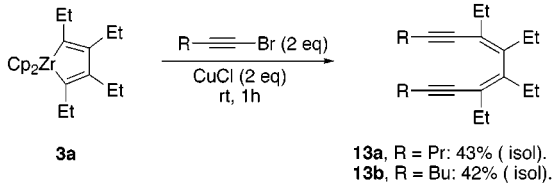
Scheme 5



Scheme 6



Scheme 7

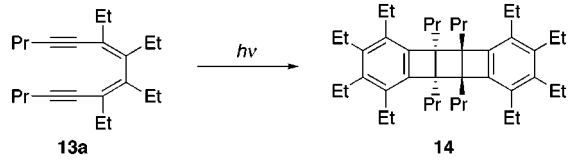


Alternatively, the selective monoalkynylation of zirconacyclopentenes was also achieved by the selective protonation of the Zr−sp^{3}C bond to give **10**,[4a−c] followed by reaction with alkynyl halide in the presence of a stoichimetric amount of CuCl (Scheme 5) to provide **9b,o,p** in good yields.[8]

Bisalkynylation of Zirconacyclopentadienes. The selective monoalkynylation of zirconacyclopentadienes, similar to the monoalkynylation of the previously mentioned zirconacycles, with 1 equiv of alkynyl halide could not be achieved, and in all cases a mixture of products was obtained. However, combination of protonation and alkynylation circumvented this difficulty. Thus, protonation of zirconacyclopentadiene **3a** with 1 equiv of *t*-BuOH gave **11**, followed by the reaction with hexynyl bromide in the presence of a stoichiometric amount of CuCl afforded **12** in good yield (Scheme 6). On the other hand, monoalkynylation of zirconacyclopentadienes could be achieved by reaction of **3** with 2 equiv of an alkynyl iodide in the presence of 2 equiv of CuCl as we already reported.[9] In this reaction, an iodinated monoalkynylation product was obtained. However, these monoalkynylations were not suitable for bisalkynylation of zirconacyclopentadienes. In the case of zirconacyclopentadienes, direct monoalkynylation was rather more promising compared with stepwise alkynylation.

Bisalkynylation of zirconacyclopentadiene **3** with 2 equiv of alkynyl bromide in the presence of 2 equiv of CuCl proceeded very fast. The corresponding dienediynes **13a**−**b** were isolated in moderate yields (Scheme 7). These results might be attributed to the instability or, rather, high reactivity of the dienediynes, which at room temperature and exposure to light were led to further reactions. For example, compound **13a** after isolation was found to be quantitatively transformed to dibenzotricycles within 1 week at room temperature, presumably by sequential intra- and intermolecular [2 + 2] cycloadditions (Scheme 8). The structure of **14** was confirmed by X-ray analysis.

Scheme 8



Experimental Section

Zirconocene dichloride was purchased from Aldrich Chemical Co., Inc. *n*-Butyllithium (1.6 M solution in hexane) was purchased from Kanto Chemicals Co. Ltd. 1,6-Heptadiene, 4-octyne, and 3-hexyne were purchased from TCI Co. Ltd. Alkynyl halides were prepared by the reaction of the corresponding alkynyllithiums with I_2 or Br_2. Dienes for the preparation of **1c**[15] and **1d**[7b] were prepared according to the previously published procedure. Other starting materials were prepared according to the standard procedures.

Zirconacycles were prepared in situ according to previously published procedures.[11−13]

General Procedure for Bisalkynylation of Bicyclic Zirconacycles. (6*R,7*R**)-1,2,3,4-Tetraethyl-6,7-bis(hept-2′-yn-1′-yl)cycloocta-1,3-diene (6h).** To a solution of **1d**, prepared in situ from Cp_2ZrCl_2 (292 mg,1 mmol),[7b] were added CuCl (198 mg, 2 mmol) and hexynyl bromide (322 mg, 2.0 mmol) at 20 °C, and the mixture was stirred for 1 h. After hydrolysis GC analysis indicated that **6h** was formed in 84% yield. Extraction with hexane followed by column chromatography on silica gel yielded 282 mg (69%) of **6h** as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.82 (t, J = 7.5 Hz, 6H), 0.90 (t, J = 7.1 Hz, 6H), 1.04 (t, J = 7.5 Hz, 6H), 1.23−1.46 (m, 12H), 1.90−2.31 (m, 18H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.53 (2C), 13.59 (4C), 18.43 (2C), 21.71 (2C), 21.92 (2C), 24.31 (2C), 25.57 (2C), 31.29 (2C), 36.87 (2C), 38.59 (2C), 78.67 (2C), 81.20 (2C), 134.94 (2C), 136.10 (2C); IR (neat) 2959, 2213, 1458, 1375, 1065 cm^{-1}; UV−vis (Et_2O) 227, 239 nm; HRMS calcd for $C_{30}H_{48}$ 408.3754, found 408.3750.

5,11-Hexadecadiyne (6e). GC yield 45%. Isolated yield 36%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.89 (t, J = 7.1 Hz, 6H), 1.26−1.59(m, 12H), 2.12−2.18(m, 8H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.58, 18.33, 18.42, 21.92. 28.27, 31.26, 79.72, 80.41; HRMS calcd for $C_{16}H_{22}$ 218.2033, found 218.2041.

(1*R,2*R**)-1,2-Bis(hept-2′-yn-1′-yl)cyclopentane (6f).** GC yield 66%. Isolated yield 53%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.91 (t, J = 7.2 Hz, 6H), 1.37−1.50 (m, 9H), 1.50−1.90 (m, 7H), 2.12−2.31 (m, 8H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.59 (2C), 18.44 (2C), 21.92 (2C), 23.45 (2C), 23.86, 31.28 (2C), 32.11 (2C), 43.68 (2C), 78.95 (2C), 80.56 (2C); HRMS calcd for $C_{19}H_{30}$ 258.2346, found 258.2348.

(1*R,2*R**)-1,2-Bis(non-2′-yn-1′-yl)cyclopentane (6g).** GC yield 58%. Isolated yield 47%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.89 (t, J = 7.2 Hz, 6H), 1.25−1.50 (m, 16H), 1.50−1.61 (m, 4H), 1.65−1.89 (m, 4H), 2.08−2.19 (m, 6H), 2.23−2.31 (m, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.02 (2C), 18.76 (2C), 22.58 (2C), 23.41 (2C), 23.85, 28.54 (2C), 29.15 (2C), 31.39 (2C), 32.09 (2C), 43.63 (2C), 78.95 (2C), 80.63 (2C); HRMS calcd for $C_{23}H_{38}$ 314.2972, found 314.2967.

General Procedure for Unsymmetric Bisalkynylation of Zirconacyclopentanes. (1*R,2*R**)-1-(Hept-2′-yn-1′-yl)-2-(3″-phenylprop-2″-yn-1″-yl)cyclopentane (6i).** Phenylethynyl bromide (181 mg, 1 mmol) and CuCl (99 mg, 1 mmol) were added to a solution of **1b**, prepared in situ from Cp_2ZrCl_2 (292 mg,1 mmol), BuLi (2 equiv), and 1,6-heptadiene (96 mg, 1 mmol), at 0 °C, and the reaction mixture was stirred for 1 h. Then were added hexynyl bromide (322 mg, 2.0 mmol) and additional CuCl (99 mg, 1 mmol); the reaction mixture was allowed to warm to room temperature and stirred for 12 h. After treatment with 3 N HCl and extraction with hexane, GC analysis showed that **6i** was formed in 61% yield. Column chromatography on silica gel (hexane) provided 156 mg (56%)

(15) Takahashi, T.; Kotora, M.; Kasai, K.; Suzuki, N. *Tetrahedron Lett.* **1994**, *35*, 5685−5688.

of the title compound as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.90 (t, J = 7.1 Hz, 3H), 1.39−1.63 (m, 8H), 1.84−1.92 (m, 4H), 2.12−2.36 (m, 4H), 2.42 (dd, J = 16.8, 6.2 Hz, 1H), 2.55 (dd, J = 16.8, 5.0 Hz, 1H), 7.24−7.40 (m, 5H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.59, 18.43, 21.93, 23.46, 23.89, 24.11, 31.26, 32.13, 32.24, 43.43, 43.80, 78.81, 80.74, 81.00, 89.34, 124.13, 127.41, 128.13 (2C), 131.54 (2C); HRMS calcd for $C_{21}H_{26}$ 278.2033, found 278.2033.

(4*R,5*S**)-1,2-Diethyl-4-(hept-2′-yn-1′-yl)-5-(3″-phenylprop-2″-yn-1″-yl)cyclohexene (6j).** GC yield 60%. Isolated yield 53%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.88−0.93 (m, 9H), 1.29−1.47 (m, 12H), 1.93−2.34 (m, 16H), 7.24−7.40 (m, 5H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.60, 14.10 (2C), 18.50, 20.04, 20.10, 21.94, 22.88, 22.89, 30.85 (2C), 31.25, 32.56 (2C), 33.14, 33.43, 36.24, 36.60, 79.00, 81.13, 81.34, 89.63, 124.21, 127.38, 128.12 (2C), 128.28, 128.47, 131.52 (2C); IR (neat) 2957, 2235, 1599, 1443, 1379, 1121, 756, 691 cm^{-1}; UV−vis (Et_2O) 241, 252 nm; HRMS calcd for $C_{30}H_{42}$ 402.3284, found 402.3274.

(6*R,7*R**)-1,2,3,4-Tetraethyl-6-(3′-phenylprop-2′-yn-1′-yl)-7-(3″-trimethylsilylprop-2″-yn-1″-yl)cycloocta-1,3-diene (6k).** Isolated yield 28%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.22 (s, 9H), 0.83 (t, J = 7.5 Hz, 3H), 0.84 (t, J = 7.5 Hz, 3H), 0.94 (t, J = 7.5 Hz, 3H), 1.04 (t, J = 7.5 Hz, 3H), 1.12−1.35 (m, 2H), 1.70−1.76 (m, 1H), 1.84−2.06 (m, 7H), 2.16−2.49 (m, 6H), 2.52 (dd, J = 16.7, 5.5 Hz, 1H), 2.81 (dd, J = 18.2, 6.8 Hz, 1H), 7.20−7.54 (m, 5H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 0.24 (3C), 12.78 (2C), 13.26, 13.42, 22.55 (2C), 25.45, 25.64, 35.21, 35.35, 41.13, 42.15, 44.84, 46.10, 96.89, 105.22, 115.85, 126.61, 127.93 (2C), 128.09 (2C), 132.49, 134.15, 135.50, 135.72, 138.60, 155.54; HRMS calcd for $C_{31}H_{44}Si$ 444.3212, found 444.3218.

General Procedure for Bisalkynylation of Zirconacyclopentenes. (3*Z*)-1,8-Diphenyl-3,4-dipropyloct-3-en-1,7-diyne (9g). To a solution of **2b**, prepared in situ from Cp_2ZrCl_2 (356 mg,1.25 mmol), EtMgBr (2 equiv), and 4-octyne (96 mg, 1 mmol), were added phenylethynyl bromide (362 mg, 2 mmol) and CuCl (198 mg, 2 mmol) at 20 °C, and the reaction mixture was stirred for 9 h and further heated to 50 °C for 6 h. The reaction mixture was quenched with 3 N HCl and extracted with hexane. Column chromatography on silica gel (hexane) afforded 180 mg of the title compound as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.92−0.97 (m, 6H), 1.44 (q, J = 7.3 Hz, 2H), 1.63 (q, J = 7.4 Hz, 2H), 2.19−2.24 (m, 4H), 2.60−2.74 (m, 4H), 7.21−7.44 (m, 10H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.78, 14.29, 18.85, 21.82, 22.15, 33.73, 33.94, 34.45, 80.87, 90.14, 90.16, 92.55, 119.79, 124.15, 124.26, 127.44, 127.56, 128.14 (2C), 128.23 (2C), 131.33 (2C), 131.55 (2C), 146.83; IR (neat) 2963, 2240, 1597, 1491, 1117, 756, 691 cm^{-1}; UV−vis (Et_2O) 251, 282 nm; HRMS calcd for $C_{26}H_{28}$ 340.2190, found 340.2194.

(7*Z*)-7,8-Dipropylhexadec-7-en-5,11-diyne (9h). GC yield 50%. Isolated yield 40%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.88−0.95 (m, 12H), 1.35−1.55 (m, 12H), 2.05−2.29 (m, 8H), 2.34 (t, J = 6.9 Hz, 2H), 2.48 (t, J = 7.5 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.58 (2C), 13.68, 14.22, 17.99, 18.47, 19.21, 21.77, 21.91, 21.96, 22.02, 31.19, 31.23, 33.62, 33.98, 34.73, 80.03, 80.09, 80.72, 92.62, 119.56, 144.70; HRMS calcd for $C_{22}H_{36}$ 300.2815, found 300.2805.

(3*E*)-1,8-Bis(trimethylsilyl)-3,4-diphenyloct-3-en-1,7-diyne (9i). GC yield 56%. Isolated yield 52%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.18(s, 9H), 0.30 (s, 9H), 2.41 (t, J = 7.6 Hz, 2H), 3.16 (t, J = 7.7 Hz, 2H), 7.04−7.18 (m, 10H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 0.03 (3C), 0.14 (3C), 18.55, 37.27, 84.91, 99.74, 105.44, 106.47, 122.18, 126.71, 127.13, 127.60 (2C), 128.02 (2C), 129.08 (2C), 129.76 (2C), 138.22, 140.05, 149.16; HRMS calcd for $C_{26}H_{32}Si_2$ 400.2043, found 400.2028.

(1′*E*)-1-(1′-Hexylhept-2′-yn-1′-ylidene)-2-(hept-2″-yn-1″-yl)cyclohexane (9j). GC yield 84%. Isolated yield 67%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.87−0.95 (m, 9H), 1.18−1.36 (m, 8H), 1.36−1.69 (m, 12H), 1.70−2.05 (m, 2H), 2.05−2.30 (m, 6H), 2.30−2.51 (m, 4H), 3.29−3.33 (m, 1H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.57 (2C), 14.02, 18.53, 19.26, 20.77, 21.47, 21.92 (2C), 22.64, 25.34, 27.47, 28.79, 28.95, 29.45, 31.19, 31.28, 31.78, 31.85, 40.12, 78.94, 80.86, 80.88, 92.36, 116.58, 146.01; HRMS calcd for $C_{26}H_{42}$ 354.3284, found 354.3278.

General Procedure for Unsymmetrical Bisalkynylation of Monocyclic Zirconacyclopentenes. (3*Z*)-1-Phenyl-3,4-diethyldodec-3-en-1,7-diyne (9k). Phenylethynyl bromide (181 mg, 1 mmol) and CuCl (99 mg, 1 mmol) were added to a solution of **2a**, prepared in situ from Cp_2ZrCl_2 (365 mg,1.25 mmol), EtMgBr (2 equiv), and 3-hexyne (84 mg, 1 mmol), at 20 °C. After 1 h were added hexynyl bromide (322 mg, 2.0 mmol) and additional CuCl (99 mg, 1 mmol), and the reaction mixture was heated to 50 °C for 6 h. After treatment of the reaction mixture with 3 N HCl and extraction with hexane, GC analysis showed that **9k** was formed in 46% yield. Column chromatography furnished 120 mg (41%) of **9k** as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.89 (t, J = 7.2 Hz, 3H), 1.01 (t, J = 7.6 Hz, 3H), 1.14 (t, J = 7.5 Hz, 3H), 1.36−1.46 (m, 4H), 2.14 (tt, J = 6.9, 2.3 Hz, 2H), 2.19 (q, J = 7.6 Hz, 2H), 2.24 (q, J = 7.6 Hz, 2H), 2.34 (t, J = 6.9, 2.3 Hz, 2H), 2.60 (t, J = 7.6 Hz, 2H), 7.25−7.45 (m, 5H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.09, 13.59, 13.68, 18.12, 18.48, 21.95, 24.65, 24.89, 31.20, 34.66, 79.84, 80.47, 89.98, 92.35, 120.38, 124.35, 127.46, 128.17 (2C), 131.29 (2C), 147.96; HRMS calcd for $C_{22}H_{28}$ 292.2191, found 292.2195.

(7*Z*)-7,8-Diethyloctadec-7-en-5,11-diyne (9l). GC yield 40%. Isolated yield 35%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.89 (t, J = 7.1, 3H), 0.93 (t, J = 7.2 Hz, 3H), 0.96 (t, J = 7.5 Hz, 3H), 1.05 (t, J = 7.6 Hz, 3H), 1.26−1.55 (m, 12H), 2.09−2.15 (m, 6H), 2.24−2.28 (m, 2H), 2.35 (t, J = 6.1 Hz, 2H), 2.48 (t, J = 7.1 Hz, 2H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.13, 13.58, 13.61, 13.99, 17.98, 18.80, 19.21, 21.97, 22.55, 24.39, 25.15, 28.55, 29.11, 31.21, 31.40, 34.44, 80.07, 80.13, 80.51, 92.71, 120.60, 145.48; HRMS calcd for $C_{22}H_{36}$ 300.2815, found 300.2809.

General Procedure for Unsymmetrical Bisalkynylation of Monoyclic Zirconacyclopentenes. (1′*E*)-1-(1′-Hexylhept-2′-yn-1′-ylidene)-2-(3″-trimethylsilylprop-2″-yn-1″-yl)cyclohexane (9m). Hexynyl bromide (161 mg, 1 mmol) and CuCl (99 mg, 1 mmol) were added to a solution of **2d**, prepared in situ from Cp_2ZrCl_2 (292 mg,1 mmol), BuLi (2 equiv), and tetradec-1-en-7-yne (192 mg, 1 mmol)[7b] at 0 °C. After 1 h were added 1-bromo-3-trimethylsilylprop-2-yne (191 mg, 1 mmol) and CuCl (99 mg, 1 mmol). The reaction mixture was stirred at the same temperature for an additional 3 h, quenched with 3 N HCl, and extracted with hexane. GC analysis indicated that **9m** was obtained in 52% yield. Column chromatography on silica gel afforded 178 mg (48%) of the title compound as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.13 (s, 9H), 0.87 (t, J = 7.0 Hz, 3H), 0.91 (t, J = 7.4 Hz, 3H), 1.1−1.35 (m, 6H), 1.39−1.56 (m, 9H), 1.74−1.85 (m, 2H), 1.93−1.95 (m, 1H), 2.09 (t, J = 7.5 Hz, 2H), 2.23−2.50 (m, 6H), 3.33−3.36 (m, 1H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 0.14 (3C), 13.63, 14.08, 19.27, 20.77, 21.94, 22.59, 22.65, 25.30, 27.40, 28.84, 28.97, 29.50, 31.13, 31.76, 31.90, 39.70, 80.79, 85.05, 92.60, 106.54, 116.88, 145.48; HRMS calcd for $C_{25}H_{42}Si$ 370.3056, found 370.3049.

(1′*E*)-1-(1′-Hexyl-3′-phenylprop-2′-yn-1′-ylidene)-2-(3″-trimethylsilylprop-2″-yn-1″-yl)cyclopentane (9n). GC yield 73%. Isolated yield 58%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.17 (s, 9H), 0.90 (t, J = 6.9 Hz, 3H), 1.25−1.40 (m, 6H), 1.52−1.63 (m, 2H), 1.65−1.75 (m, 1H), 1.80−1.95 (m, 3H), 2.17 (t, J = 7.7 Hz, 2H), 2.33−2.42 (m, 3H), 2.76 (dd, J = 17.8, 3.8 Hz, 1H), 3.10−3.11 (m, 1H), 7.25−7.46 (m, 5H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 0.18 (3C), 14.07, 22.63, 24.00, 24.14, 28.27, 28.85, 31.12, 31.22, 31.78, 33.35, 43.91, 84.62, 89.96, 92.66, 106.93, 115.73, 124.24, 127.53, 128.20 (2C), 131.26 (2C), 154.90; HRMS calcd for $C_{26}H_{36}Si$ 376.2586, found 376.2573. Anal. Calcd for $C_{26}H_{36}Si$: C, 82.91; H, 9.63. Found: C, 82.37, H, 9.64.

Monoalkynylkation of Zirconacyclopentadiene 3 via Protonolysis. (3*E*)-3-Ethyl-4-propyldodec-3-en-5-yne (9o). *t*-BuOH (81 mg, 1.1 mmol) was added to a solution of **2b**, prepared in situ from Cp_2ZrCl_2 (365 mg,1.25 mmol), EtMgBr (2 equiv), and 3-hexyne (84 mg, 1 mmol), at 20 °C, and the mixture was stirred for 3 h. After addition of hexynyl bromide

(161 mg, 1 mmol), CuCl (99 mg, 1 mmol), and stirring for additional 3 h, the reaction mixture was quenched with 3 N HCl and extracted with hexane. GC analysis showed that **9o** was formed in 83% yield. Column chromatography on silica gel (hexane) afforded 150 mg (68%) of the title compound as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.88−0.94 (m, 9H), 1.00 (t, J = 7.5 Hz, 3H), 1.37−1.55 (m, 8H), 2.06 (q, J = 7.6 Hz, 4H), 2.31 (q, J = 7.5 Hz, 4H), 2.28−2.25 (m, 4H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.85, 13.52, 13.70, 14.25, 19.20, 21.88, 21.94, 22.09, 28.04, 31.30, 33.01, 34.04, 80.99, 91.75, 117.73, 147.56; HRMS calcd for $C_{16}H_{28}$ 220.2190, found 220.2189.

(3*E*)-1,3,4-Triphenylhex-3-en-1-yne (9p). GC yield 64%. Isolated yield 49%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.10 (t, J = 7.5 Hz, 3H), 2.98 (q, J = 7.5 Hz, 2H), 7.02−7.48 (m, 15H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.61, 31.32, 90.30, 93.74, 120.04, 123.76, 126.51, 126.84, 127.61, 127.89 (2C), 127.93 (2C), 128.24 (2C), 129.09 (2C), 129.78 (2C), 131.35 (2C), 138.93, 140.55, 151.72; HRMS calcd for $C_{24}H_{20}$ 308.1564, found 308.1559.

Monoalkynylkation of Zirconacyclopentadiene 3 via Protonolysis. (1*E*,3*Z*)-1,2,3,4-Tetraethyldodeca-1,3-dien-5-yne (12). A solution of **3**, prepared in situ from Cp_2ZrCl_2 (292 mg,1 mmol), BuLi (2 equiv), and 3-hexyne (164 mg, 2 mmol), was treated with *t*-BuOH (81 mg,1.1 mmol) at 20 °C for 12 h. Then were added hexynyl bromide (161 mg, 1 mmol) and CuCl (99 mg, 1 mmol), and the reaction mixture was stirred for 3 h. After quenching with 3 N HCl and extraction with hexane, GC analysis indicated that **12** was formed in 66% yield. Column chromatography on silica gel gave 133 mg (54%) of **12** as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.88−1.01 (m, 12H), 1.08 (t, J = 7.5 Hz, 3H), 1.34−1.45 (m, 4H), 2.06−2.18 (m, 8H), 2.26 (t, J = 6.8 Hz, 3H), 5.22 (t, J = 7.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.07, 13.11, 13.58, 13.68, 14.38, 19.21, 21.05, 21.91, 22.49, 23.85, 25.69, 31.22, 82.15, 90.21, 119.93, 129.92, 141.02, 149.31; IR (neat) 2973, 2202, 1717, 1460, 1381, 1119 cm^{-1}; UV−vis (Et_2O) 211 (sh) nm; HRMS calcd for $C_{18}H_{30}$ 246.2346, found 246.2345.

General Procedure for the Bisalkynylkation of Zirconacyclopentadienes. (6*Z*,8*Z*)-6,7,8,9-Tetraethyltetradeca-6,8-dien-4,10-diyne (13a). To a solution of **3**, prepared in situ from Cp_2ZrCl_2 (292 mg,1 mmol), BuLi (2 equiv), and 3-hexyne (164 mg, 2 mmol), were added pentynyl bromide (294 mg, 2 mmol) and CuCl (198 mg, 2 mmol), at 20 °C. The reaction mixture was quenched after 1 h with 3 N HCl and extracted with hexane. Column chromatography on silica gel (hexane) provided 128 mg (43%) of the title compound as a colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.97 (t, J = 7.0 Hz, 6H), 0.98 (t, J = 7.0 Hz, 6H), 1.09 (t, J = 7.5 Hz, 6H), 1.49 (qt, J = 7.2, 7.2 Hz, 4H), 2.13−2.24 (m, 12H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.98, 13.53, 13.55, 21.70, 22.62, 24.63, 25.57, 82.33, 89.87, 121.45, 146.90; HRMS calcd for $C_{22}H_{34}$ 298.2659, found 298.2669.

(7*Z*,9*Z*)-7,8,9,10-Tetraethylhexadeca-7,9-dien-5,11-diyne (13b). Isolated yield 42%. A colorless liquid: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.89 (t, J = 7.5 Hz, 6H), 0.97 (t, J = 7.5 Hz, 6H), 1.08 (t, J = 7.4 Hz, 6H), 1.40−1.46 (m, 8H), 2.12−2.26 (m, 12H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.97, 13.55, 13.69, 19.25, 21.89, 24.58, 25.52, 31.25, 82.10, 89.88, 121.34, 146.83; HRMS calcd for $C_{24}H_{38}$ 326.2972; found 326.2981.

Formation of Diels−Alder Reaction Product (14) from 13a. Standing neat liquid **13a** in a flask for 1 week at 20 °C resulted in quantitative formation of a cystalline material. This material was analyzed without further purification: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.75 (t, J = 7.3 Hz, 12H), 0.90−1.10 (m, 4H), 1.18 (t, J = 7.4 Hz, 12H), 1.24 (t, J = 7.3 Hz, 12H), 1.1−1.3 (m, 4H), 1.47 (dt, J = 13.3, 4.6 Hz, 4H), 1.71 (dt, J = 13.3, 4.6 Hz, 4H), 2.52−2.61 (m, 8H), 2.62−2.74 (m, 8H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 15.13, 15.51, 16.51, 19.92, 21.74, 23.16, 33.09, 62.19, 135.26, 139.40, 144.44; IR (Nujol) 2870, 1771, 1462, 1377, 1053 cm^{-1}; UV−vis (Et_2O) 224, 291 nm; HRMS calcd for $C_{44}H_{68}$ 596.5318, found 596.5329. Anal. Calcd for $C_{44}H_{68}$: C, 88.52; H, 11.48. Found: C, 88.40, H, 11.47.

Acknowledgment. We thank the Ministry of Education, Science, Sport and Culture, Japan, for support of a part of this study.

Supporting Information Available: ORTEP diagram, tables of crystallographic data, atomic coordinates, thermal parameters and bond lengths and angles for **14**, experimental procedures and spectra data for **6a**−**d** and **9a**−**f**, spectra of **6a**−**k**, **9a**−**p**, **12**, **13b**, and **14**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO0005417