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Strictly "Pair"-Selective and Economical Synthesis of Conjugated Diynes via Pd-Catalyzed Reaction of Terminal Alkynes with 1,1-Dichloroethylene, Elimination with LDA, and Subsequent Transformations

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Abstract:

Various unsymmetrically substituted conjugated diynes can be synthesized in a completely "pair"-selective manner via Pd-catalyzed reaction of terminal alkynes with 1,1-dichloroethylene in the presence of $Pd(PPh_3)_4$ followed by elimination with 2 equiv of lithium diisopropylamide (LDA), zincation with $ZnBr_2$ or $ZnCl_2$, and Pd-catalyzed cross-coupling with aryl and alkenyl iodides and bromides. The desired unsymmetrically substituted conjugated diynes have been obtained in >80% yields except in two cases where an alkenylzinc reagent generated in situ from (*E*)-3-iodo-2-propenol was used. The use of 1,1-dichloroethylene renders this method more economical than those involving 1,2-dihaloethylenes previously reported.

Introduction

Conjugated diynes are frequently encountered part structures of natural products[1] and compounds of material chemical interest.[2] These compounds, in the past, have been most widely synthesized by the Cadiot−Chodkiewicz reaction[3] (eq 1, Scheme 1). More recently, various procedures for Pd-catalyzed alkynyl−alkynyl coupling[4] have been reported as alternative routes. Although these alkynyl−alkynyl coupling reactions are satisfactory in many cases, they also suffer from cross-homo scrambling leading to the formation of two homodiynes and low product yields in many other cases. None of them has been shown to be widely applicable in a selective and satisfactory manner. The authors' group developed a strictly "pair"-selective route to conjugated diynes via Pd-catalyzed alkynylation of ICH═CHCl[5] and ICH═CHBr,[5b] which has been shown to be widely applicable, selective, and generally satisfactory[6] (eq 2, Scheme 1). As selective and widely satisfactory as the alkynyl−alkenyl coupling protocol[5,6] is, the current costs of 1,2-dihaloethylenes are relatively high. With the goal of developing a more economical route to conjugated diynes, our attention was drawn to the Pd-catalyzed Sonogashira alkynylation[7] of inexpensive 1,1-dichloroethylene[8] (eq 3, Scheme 2). To the best of our knowledge, however, the synthesis of conjugated diynes via 2-chloro-1-en-3-ynes (**1**) prepared by this route has not been demonstrated in the literature.[9]

Results and Discussion

1. Preparation of 2-Chloro-1-en-3-ynes by the Pd-Catalyzed Alkynylation of 1,1-Dichloethylene. Comparison of the Sonogashira and Negishi Protocols. In view of the favorable results of the synthesis of 2-chloro-1-en-3-ynes previously reported,[8] *n*-HexC≡CH, PhC≡CH, and Me_3SiC≡CH were chosen as three representative terminal alkynes and converted into the corresponding 2-chloro-1-en-3-ynes **1a**−**1c** by their reaction with 5 molar equiv of 1,1-dichloroethylene according to the literature procedure.[8] The desired compounds were obtained in 66%, 82%, and 69% yields by GLC, respectively. These yield figures are somewhat lower than those reported, but the reported results were reproduced more or less as described. The main byproducts were the dialkynylation products. On the other hand, the Negishi alkynylation protocol[10] with the use of alkynylzinc derivatives led to extensive formation of the

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(6) For a related paper, see: Kende, A. S.; Smith, C. A. *J. Org. Chem*. **1988**, *53*, 2655.

(7) (a) For a recent review, see: Sonogashira, K. In *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E., Ed.; Wiley-Interscience: New York, 2002; p 493. (b) For a seminal paper, see: Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett*. **1975**, *16*, 4467.

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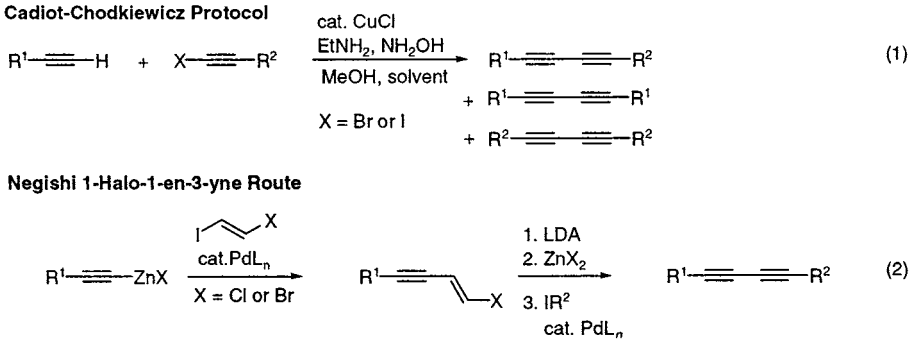
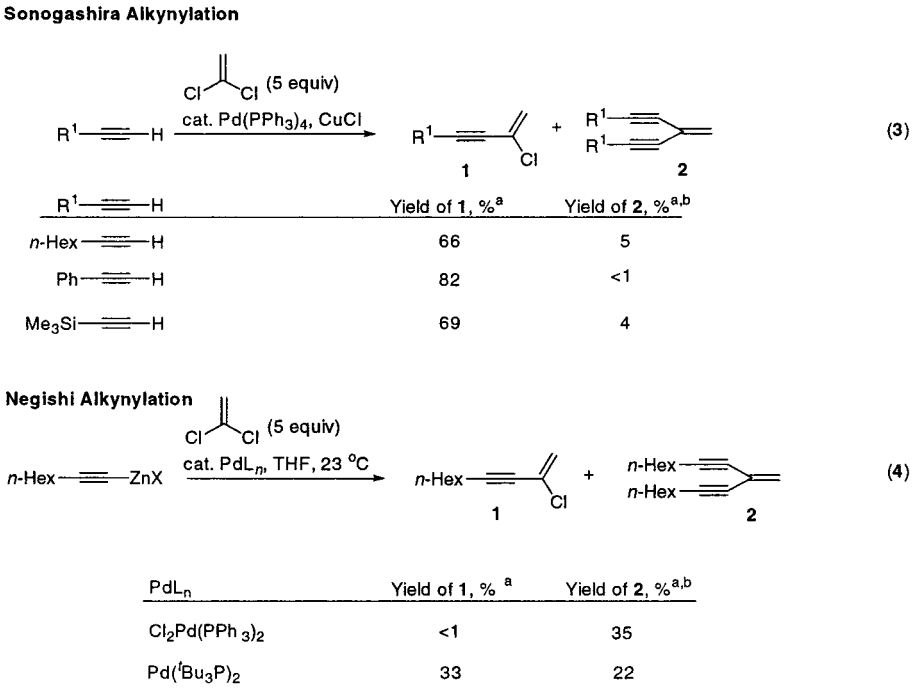
Scheme 1



Scheme 2[a,b]



R^1—≡—H	Yield of **1**, %[a]	Yield of **2**, %[a,b]
n-Hex—≡—H	66	5
Ph—≡—H	82	<1
Me_3Si—≡—H	69	4

PdL_n	Yield of **1**, %[a]	Yield of **2**, %[a,b]
$Cl_2Pd(PPh_3)_2$	<1	35
$Pd(^tBu_3P)_2$	33	22

[a] By GLC. [b] Formation of 1% of **2** accounts for 2% of the starting alkyne.

dialkynylation products along with relatively low yields of the desired products. The best results were obtained by using $Pd(^tBu_3P)_2$[11] as a catalyst, as shown in eq 4, Scheme 2. Clearly, the high intrinsic reactivity of organozincs must be detrimental to this reaction. Since the corresponding Pd-catalyzed alkynylation of 2-substituted 1,1-dichloro-1-alkenes[12] has been shown to proceed well and better under Negishi conditions[10] than under Sonogashira conditions,[7] it is advisable to experimentally determine the optimal protocol for a given transformation of this type.

2. Conversion of 2-Chloro-1-en-3-ynes to Conjugated Diynes via Elimination with LDA and Pd-Catalyzed Alkynylation Using the Negishi Protocol. Treatment of 2-chloro-1-en-3-ynes (**1a**−**1c**) with 2.0 equiv of LDA (lithium diisoproylamide) in THF at −78 °C for 30 min and then at −30 °C for another 30 min followed by addition of dry $ZnBr_2$ or $ZnCl_2$ (−30 to 0 °C, 30 min) produced the corresponding 1,3-diynylzinc derivatives **3a**−**3c** in nearly quantitative yields, as judged by the nearly quantitative formation of 1-deuterio-1,3-diynes upon deuteriolysis with D_2O. (Scheme 3). 1,3-Diynes, in principle, can be converted to a wide variety of unsymmetrically or symmetrically disubstituted conjugated diynes by a variety of known reactions. In this work, however, we opted for the preparation of unsymmetrically disubstituted conjugated diynes by Pd-catalyzed alkynylation of aryl and alkenyl halides with alkynylzincs.[10]

As summarized in Table 1, all of the reactions carried out with two aryl and five alkenyl iodides and bromides in the presence of 5 mol % of $Pd(PPh_3)_4$ in THF at 23 °C proceeded cleanly to produce the desired 1,3-diynes in over 80% isolated yields except in the reactions of (*E*)-3-iodo-2-propenol, where the product yields were 67% and 71%. As might be readily expected, there was no sign of the formation of conjugated homodiynes throughout this study.

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Scheme 3

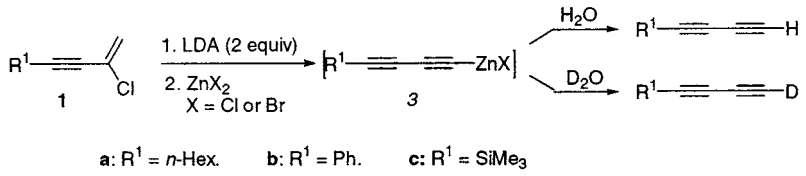
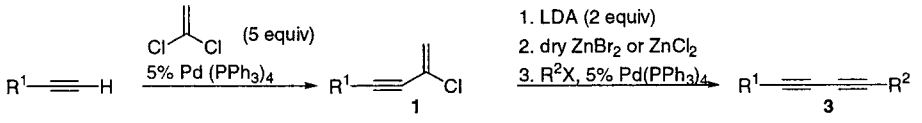


Table 1. **Strictly "Pair"-Selective Synthesis of Unsymmetrically Disubstituted Conjugated Diynes via Pd-Catalyzed Cross Coupling and *β*-Elimination**



Entry	R^1—≡—H	XR^2	R^1—≡—R^2 (3)[a]		Isolated yield of **3** based on **1**, %
i	*n*-Hex—≡—H	IPh	*n*-Hex—≡—Ph	**3i**	92
ii	*n*-Hex—≡—H	I, Hex-*n*	*n*-Hex—≡—Hex-*n*	**3ii**	88
iii	*n*-Hex—≡—H	I, OH	*n*-Hex—≡—OH	**3iii**	67
iv	*n*-Hex—≡—H	Br, COOMe	*n*-Hex—≡—COOMe	**3iv**	90
v	*n*-Hex—≡—H	Br, $SiMe_3$	*n*-Hex—≡—$SiMe_3$	**3v**	85
vi	Ph—≡—H	I, S	Ph—≡—S	**3vi**	82
vii	Ph—≡—H	I, OH	Ph—≡—OH	**3vii**	71
viii	Ph—≡—H	Br, COOMe	Ph—≡—COOMe	**3viii**	93
ix	Ph—≡—H	I, Br	Ph—≡—Br	**3ix**	89
x	Ph—≡—H	Br, $SiMe_3$	Ph—≡—$SiMe_3$	**3x**	87
xi	Me_3Si—≡—H	Br, COOMe	Me_3Si—≡—COOMe	**3xi**	92
xii	Me_3Si—≡—H	I, Br	Me_3Si—≡—Br	**3xii**	83
xiii	Me_3Si—≡—H	Br, $SiMe_3$	Me_3Si—≡—$SiMe_3$	**3xiii**	86

[a] All stereodefined products are >98−99% *E* by ^{13}C and ^1H NMR spectroscopy except for **3vii** which is 91% *E*.

The reaction of 1-octyne with 5 equiv of (*E*)-1,2-dichloroethylene in benzene in the presence of 5 mol % each of $Pd(PPh_3)_4$ and CuI as well as *n*-$BuNH_2$ (1.5 equiv) produced (*E*)-1-chloro-1-decen-3-yne in 78% yield by GLC along with the dialkynylation product (11%), as previously reported.[13] Sequential treatment of the chloroenyne obtained previously with *n*-BuLi (2.0 equiv), dry $ZnBr_2$ (1.1 equiv), PhI (1 equiv), and 5 mol % of $Pd(PPh_3)_4$ in THF gave 1-phenyl-1,3-decadiyne in 89% yield by GLC. Similarly, the corresponding cross-coupling reaction with methyl (*E*)-3-bromo-2-methyl-2-propenoate gave the expected cross-coupling product in 91% yield by GLC, while that with 1-iodo-1-octyne produced 7,9,11-octadecatriyne in 72% yield by GLC. These results are roughly comparable to those observed with 1,1-dichloroethylene. However, 1,2-dichloroethylene appears to be significantly more expensive than 1,1-dichloroethylene (their prices per 100 g in a recent Aldrich catalog are $151.80 and $17.50, respectively).

In summary, the two-step synthesis of conjugated diynes reported herein promises to be not only clean, selective,

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widely applicable, and generally satisfactory but also the most economical among all known methods.

Experimental Section

General Methods. All reactions were run under Ar atmosphere. Reactions were monitored by GLC analysis of reaction aliquots. GLC analysis was performed on an HP6890 gas chromatograph by using an HP-5 capillary column (30 m × 0.32 mm, 0.5 μm film). GLC yields were determined by using mesitylene as the internal standard. Column chromatography was carried out on 230−400 mesh silica gel. ^{1}H and ^{13}C NMR spectra were recorded on a Varian Inova-300 spectrometer. Isomeric purity of the compounds reported herein was determined by ^{1}H and ^{13}C NMR spectroscopy. THF is distilled from sodium/benzophenone. $ZnBr_2$ was flame-dried at <1 mmHg.

Pd-Catalyzed Alkynylation of 1,1-Dichloroethylene under the Sonogashira Conditions. (a) 2-Chloro-1-decen-3-yne.[8] **Representative Procedure.** The following experiments were carried out according to the literature procedure.[8] To a solution of $Pd(PPh_3)_4$ (1.44 g, 1.25 mmol) in benzene (40 mL) was added 1,1-dichloroethylene (12.1 g, 125 mmol), and the reaction mixture was stirred at 23 °C for 15 min. To this were added a mixture of 1-octyne (2.76 g, 25 mmol) and *n*-$BuNH_2$ (2.74 g, 37.5 mmol) and then copper iodide (0.24 g, 1.25 mmol). The reaction mixture was stirred for 5 h, and an aliquot was analyzed by GLC with mesitylene as an internal standard. Analysis indicated the formation of the title compound in 66% yield along with the dialkynylation product in 5% yield. Then, the reaction mixture was hydrolyzed with aqueous ammonium chloride, extracted with Et_2O, dried over $MgSO_4$, filtered, and concentrated. Distillation gave 2.56 g (60%) of the title compound as a colorless liquid: bp 78−80 °C (5 mmHg); ^{1}H NMR ($CDCl_3$) 0.93 (t, J = 6.6 Hz, 3 H), 1.3−1.6 (m, 8 H), 2.38 (t, J = 7.0 Hz, 2 H), 5.55 (s, 1 H), 5.58 (s, 1 H) ppm; ^{13}C NMR ($CDCl_3$) 14.24, 19.45, 22.75, 28.36, 28.79, 31.52, 77.81, 93.03, 120.51, 121.03 ppm.

(b) 2-Chloro-4-phenyl-1-buten-3-yne.[8] The title compound was prepared from phenylacetylene (2.55 g, 25 mmol) and 1,1-dichloroethylene (12.1 g, 125 mmol). Distillation afforded 3.25 g (80%) of the title compound as a yellow liquid: yield by GLC, 82%; bp 95−97 °C (5 mmHg); ^{1}H NMR ($CDCl_3$) 5.73 (d, J = 1.0 Hz, 1 H), 5.80 (d, J = 1.0 Hz, 1 H), 7.35−7.5 (m, 5 H) ppm; ^{13}C NMR ($CDCl_3$) 85.95, 90.87, 120.73, 121.86, 122.21, 128.74 (2 C), 129.58, 132.10 (2 C) ppm.

(c) 2-Chloro-4-trimethylsilyl-1-buten-3-yne.[8] The title compound was prepared from trimethylsilylacetylene (2.46 g, 25 mmol) and 1,1-dichloroethylene (12.1 g, 125 mmol). Distillation afforded 2.46 g (62%) of the title compound as a colorless liquid: GLC in 69% yield along with the dialkynylation product in 4% yield; bp 57−59 °C (20 mmHg); ^{1}H NMR ($CDCl_3$) 0.24 (s, 9 H), 5.64 (d, J = 1.1 Hz, 1 H), 5.72 (d, J = 1.1 Hz, 1 H) ppm; ^{13}C NMR ($CDCl_3$) −0.29 (3 C), 96.78, 100.44, 120.45, 122.55 ppm.

Pd-Catalyzed Alkynylation of 1,1-Dichloroethylene under the Negishi Conditions. 2-Chloro-1-decen-3-yne. Representative Procedure. To a solution of 1-octyne (110 mg, 1.0 mmol) in THF (4 mL) was added *n*-BuLi (0.4 mL of 2.5 M hexane solution, 1.0 mmol) at −78 °C. The reaction mixture was stirred at −78 °C for 30 min, treated with a solution of anhydrous $ZnBr_2$ (223 mg, 1.0 mmol) in THF (1 mL), and warmed to 0 °C over 30 min. 1,1-Dichloroethylene (485 mg, 5.0 mmol) and $Pd(^tBu_3P)_2$ (26 mg, 0.05 mmol) was added to the reaction mixture at 0 °C, which was then stirred at 23 °C for 6 h. Analysis of an aliquot of the reaction mixture by GLC indicated the formation of the title compound in 33% yield along with the dialkynylation product formed in 22% yield.

A second reaction used $Pd(PPh_3)_2Cl_2$ (35 mg, 0.05 mmol) as catalyst. The reaction mixture was stirred at 50 °C for 4 h. Analysis of an aliquot of the reaction mixture by GLC indicated the formation of the dialkynylation product in 35% yield.

Conversion of 2-Chloro-1-en-3-ynes to Conjugated Unsymmetrically Substituted Diynes *via* Elimination with LDA and Pd-Catalyzed Negishi Coupling. (i) 1-Phenyl-1,3-decadiyne.[5b] **Representative Procedure.** To a solution of *N*,*N*-diisopropylamine (223 mg, 2.2 mmol) in 4 mL of THF was added *n*-BuLi (0.88 mL of 2.5 M solution in hexane, 2.2 mmol) at 0 °C in a flame-dried flask under Ar atmosphere. After 30 min, 2-chloro-1-decen-3-yne (187 mg, 1.1 mmol) in 1 mL of THF was added to the LDA solution prepared previously by *cannula* at −78 °C. The reaction mixture was stirred first at −78 °C for 30 min and then at −30 °C for 30 min, treated with a solution of anhydrous $ZnBr_2$ (270 mg, 1.2 mmol) in THF (1 mL), and warmed to 0 °C over 30 min. Iodobenzene (204 mg, 1.0 mmol) and $Pd(PPh_3)_4$ (58 mg, 0.05 mmol) were added to the reaction mixture at 0 °C, which was then stirred at 23 °C for 3 h. The reaction mixture was diluted with Et_2O, washed with aqueous NH_4Cl and then with aqueous $NaHCO_3$, dried over $MgSO_4$, filtered, and concentrated. Chromatography on silica gel (hexane) gave 193 mg (92%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.95 (t, J = 6.6 Hz, 3 H), 1.3−1.65 (m, 8 H), 2.41 (t, J = 7.0 Hz, 2 H), 7.3−7.5 (m, 5 H) ppm; ^{13}C NMR ($CDCl_3$) 14.35, 19.89, 22.84, 28.56, 28.88, 31.62, 65.42, 74.80, 74.98, 85.15, 122.45, 128.63 (2 C), 129.07, 132.77 (2 C) ppm.

(ii) (*E*)-7-Octadecen-9,11-diyne.[5b] The title compound was prepared from 2-chloro-1-decen-3-yne (187 mg, 1.1 mmol) and (*E*)-1-iodo-1-octene (238 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane) afforded 215 mg (88%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.9−0.95 (m, 6 H), 1.3−1.6 (m, 16 H), 2.16 (q, J = 7.0 Hz, 2 H), 2.35 (t, J = 6.7 Hz, 2 H), 5.55 (d, J = 15.9 Hz, 1 H), 6.3−6.4 (m, 1 H) ppm; ^{13}C NMR ($CDCl_3$) 14.28, 14.29, 19.79, 22.79, 22.84, 28.57, 28.80 (2 C), 29.02, 31.58, 31.89, 33.49, 65.51, 73.15, 74.23, 83.82, 108.92, 148.38 ppm.

(iii) (*E*)-2-Tridecen-4,6-diyn-1-ol.[14] To a solution of *N*,*N*-diisopropylamine (223 mg, 2.2 mmol) in 4 mL of THF was added *n*-BuLi (0.88 mL of 2.5 M solution in hexane, 2.2 mmol) at 0 °C in a flame-dried flask under Ar atmosphere.

(14) For the synthesis of the *Z* isomer only, see: Zeni, G.; Menezes, P. H.; Moro, A. V.; Braga, A. L.; Silveira, C. C.; Stefani, H. A. *Synlett* **2001**, 1473.

After 30 min, 2-chloro-1-decen-3-yne (187 mg, 1.1 mmol) in 1 mL of THF was added to the LDA solution prepared previously by *cannula* at −78 °C. The reaction mixture was stirred first at −78 °C for 30 min and then at −30 °C for 30 min. Anhydrous $ZnBr_2$ (270 mg, 1.2 mmol) in THF (1 mL) was added to the reaction mixture at −30 °C and warmed to 0 °C over 30 min. A solution of (*E*)-3-iodo-2-propen-1-ol (184 mg, 1.0 mmol) in 2 mL of THF was treated with Et_2Zn (74 mg, 0.6 mmol) at 0 °C under Ar atmosphere. After 30 min, the reaction mixture was transferred by *cannula*, and 3 mL of DMF were added by syringe. The mixture was treated with $Pd(PPh_3)_4$ (58 mg, 0.05 mmol) into the first flask at 0 °C, which was then stirred at 60 °C for 6 h. The reaction mixture was diluted with Et_2O, washed with aqueous NH_4Cl and then with aqueous $NaHCO_3$, dried over $MgSO_4$, filtered, and concentrated. Purification by column chromatography (silica gel, hexane/EtOAc = 80/20, v/v) afforded 127 mg (67%) of the title compound as a yellow oil: ^{1}H NMR ($CDCl_3$) 0.93 (t, J = 7.4 Hz, 3 H), 1.3−1.6 (m, 9 H), 2.36 (t, J = 6.7 Hz, 2 H), 4.28 (d, J = 3.5 Hz, 2 H), 5.85 (d, J = 16.0 Hz, 1 H), 6.35−6.45 (m, 1 H) ppm; ^{13}C NMR ($CDCl_3$) 14.29, 19.81, 22.76, 28.46, 28.79, 31.54, 63.65, 65.25, 73.13, 75.34, 85.00, 109.56, 144.85 ppm. HRMS: calculated for $C_{13}H_{18}O$, 190.1358; found, 190.1363.

(iv) Methyl (*E*)-2-Methyl-2-tridecen-4,6-diynoate.[5b] The title compound was prepared from 2-chloro-1-decen-3-yne (187 mg, 1.1 mmol) and methyl (*E*)-3-bromo-2-methyl-2-propenoate (179 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane/EtOAc = 95/5, v/v) afforded 209 mg (90%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.93 (t, J = 6.4 Hz, 3 H), 1.3−1.6 (m, 8 H), 2.13 (s, 3 H), 2.41 (t, J = 6.9 Hz, 2 H), 3.80 (s, 3 H), 6.66 (s, 1 H) ppm; ^{13}C NMR ($CDCl_3$) 14.24, 15.86, 19.99, 22.74, 28.33, 28.79, 31.50, 52.38, 65.16, 71.30, 86.39, 89.41, 119.03, 141.97, 167.41 ppm.

(v) (*E*)-1-Trimethylsilyl-3-tetradecen-1,5,7-triyne. The title compound was prepared from 2-chloro-1-decen-3-yne (187 mg, 1.1 mmol) and (*E*)-1-bromo-4-trimethylsilyl-1-buten-3-yne (203 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane) afforded 218 mg (85%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.23 (s, 9 H), 0.93 (t, J = 6.6 Hz, 3 H), 1.3−1.6 (m, 8 H), 2.38 (t, J = 6.9 Hz, 2 H), 6.07 (d, J = 16.2 Hz, 1 H), 6.14 (d, J = 16.2 Hz, 1 H) ppm; ^{13}C NMR ($CDCl_3$) −0.03 (3 C), 14.29, 19.95, 22.76, 28.39, 28.79, 31.53, 65.28, 73.23, 80.25, 87.86, 102.13, 103.09, 121.17, 123.52 ppm. HRMS: calculated for $C_{17}H_{24}Si$, 256.1647; found, 256.1647.

(vi) 1-Phenyl-4-(2-thienyl)-1,3-butadiyne.[15] The title compound was prepared from 2-chloro-4-phenyl-1-buten-3-yne (179 mg, 1.1 mmol) and 2-iodothiophene (210 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane) afforded 171 mg (82%) of the title compound as a yellow oil: ^{1}H NMR ($CDCl_3$) 7.0−7.6(m, 8 H) ppm; ^{13}C NMR ($CDCl_3$) 74.18, 75.00, 78.42, 84.00, 121.96, 122.36, 127.55, 128.83 (2 C), 129.09, 129.68, 132.80 (2 C), 134.65 ppm.

(15) Ziegler, C. B., Jr.; Harris, S. M.; Baldwin, J. E. *J. Org. Chem.* **1987**, *52*, 443.

(vii) (*E*)-7-Phenyl-2-hepten-4,6-diyn-1-ol.[16] To a solution of *N*,*N*-diisopropylamine (223 mg, 2.2 mmol) in 3 mL of THF was added *n*-BuLi (0.88 mL of 2.5 M solution in hexane, 2.2 mmol) at 0 °C in a flame-dried flask under Ar atmosphere. After 30 min, 2-chloro-4-phenyl-1-buten-3-yne (179 mg, 1.1 mmol) in 1 mL of THF was added to the LDA solution prepared previously by *cannula* at −78 °C. The reaction mixture was stirred first at −78 °C for 30 min and then at −30 °C for 30 min. Anhydrous $ZnBr_2$ (270 mg, 1.2 mmol) in THF (1 mL) was added to the reaction mixture at −30 °C, which warmed to 0 °C over 30 min. A solution of (*E*)-3-iodo-2-propen-1-ol (184 mg, 1.0 mmol) in 2 mL of THF was treated with Et_2Zn (74 mg, 0.6 mmol) at 0 °C under Ar atmosphere. After 30 min, the reaction mixture was transferred by *cannula*, and 3 mL of DMF were added by syringe. The mixture was treated with $Pd(PPh_3)_4$ (58 mg, 0.05 mmol) into the first flask at 0 °C, which was then stirred at 60 °C for 6 h. The reaction mixture was diluted with Et_2O, washed with aqueous NH_4Cl and then with aqueous $NaHCO_3$, dried over $MgSO_4$, filtered, and concentrated. Purification by column chromatography (silica gel, hexane/EtOAc = 80/20, v/v) afforded 129 mg (71%) of the title compound as a yellow oil: ^{1}H NMR ($CDCl_3$) 1.51 (s, 1 H), 4.31 (s, 2 H), 5.94 (d, J = 14.0 Hz, 1 H), 6.4−6.5 (m, 1 H), 7.3−7.5 (m, 5 H) ppm; ^{13}C NMR ($CDCl_3$) 62.96, 74.16, 74.77, 80.11, 81.59, 109.17, 122.03, 128.68 (2 C), 129.45, 132.73 (2 C), 145.75 ppm.

(viii) Methyl (*E*)-2-Methyl-7-phenyl-2-hepten-4,6-diynoate. The title compound was prepared from 2-chloro-4-phenyl-1-buten-3-yne (179 mg, 1.1 mmol) and methyl (*E*)-3-bromo-2-methyl-2-propenoate (179 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane/EtOAc = 95/5, v/v) afforded 208 mg (93%) of the title compound as a yellow oil: ^{1}H NMR ($CDCl_3$) 2.18 (s, 3 H), 3.82 (s, 3 H), 6.75 (s, 1 H), 7.35−7.5 (m, 5 H) ppm; ^{13}C NMR ($CDCl_3$) 16.09, 52.49, 73.84, 78.10, 85.57, 85.69, 118.62, 121.64, 128.77 (2 C), 129.86, 132.79 (2 C), 142.63, 167.25 ppm. HRMS: calculated for $C_{15}H_{12}O_2$, 224.0837; found, 224.0838.

(ix) (*E*)-1-Bromo-6-phenyl-1-hexen-3,5-diyne. The title compound was prepared from 2-chloro-4-phenyl-1-buten-3-yne (163 mg, 1.0 mmol) and (*E*)-1-iodo-2-bromoethylene (350 mg, 1.5 mmol). Purification by column chromatography (silica gel, hexane) afforded 205 mg (89%) of the title compound as a yellow oil: ^{1}H NMR ($CDCl_3$) 6.38 (d, J = 14.2 Hz, 1 H), 6.17 (d, J = 14.2 Hz, 1 H), 7.3−7.55 (m, 5 H) ppm; ^{13}C NMR ($CDCl_3$) 73.92, 76.48, 78.13, 83.12, 116.93, 121.73, 122.66, 128.76 (2 C), 129.53, 132.80 (2 C) ppm. HRMS: calculated for $C_{12}H_7Br$, 229.9731; found, 229.9725.

(x) (*E*)-1-Trimethylsilyl-8-phenyl-3-octen-1,5,7-triyne. The title compound was prepared from 2-chloro-4-phenyl-1-buten-3-yne (179 mg, 1.1 mmol) and (*E*)-1-bromo-4-trimethylsilyl-1-buten-3-yne (203 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane) afforded 216 mg (87%) of the title compound as a yellow oil: ^{1}H NMR ($CDCl_3$) 0.25 (s, 9 H), 6.17 (d, J = 16.0 Hz, 1 H), 6.23 (d,

(16) Jones, S. E. R. H.; Safe, S.; Thaller, V. *J. Chem. Soc. C* **1967**, 1038.

J = 16.0 Hz, 1 H), 7.3−7.55 (m, 5 H) ppm; ^{13}C NMR ($CDCl_3$) −0.01 (3 C), 74.04, 79.66, 80.05, 84.29, 103.06, 120.79, 121.81, 124.17, 128.73 (2 C), 129.69, 132.78 (2 C) ppm. HRMS: calculated for $C_{17}H_{16}Si$, 248.1021; found, 248.1021.

(xi) Methyl (*E*)-2-Methyl-7-trimethylsilyl-2-hepten-4,6-diynioate. The title compound was prepared from 2-chloro-4-trimethylsilyl-1-buten-3-yne (174 mg, 1.1 mmol) and methyl (*E*)-3-bromo-2-methyl-2-propenoate (179 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane) afforded 202 mg (92%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.26 (s, 9 H), 2.14 (s, 3 H), 3.80 (s, 3 H), 6.65 (s, 1 H) ppm; ^{13}C NMR ($CDCl_3$) −0.32 (3 C), 15.99, 52.43, 73.07, 85.61, 87.48, 95.09, 118.19, 143.31, 167.08 ppm. HRMS: calculated for $C_{12}H_{16}O_2Si$, 220.0920; found, 220.0924.

(xii) (*E*)-1-Bromo-6-trimethylsilyl-1-hexen-3,5-diyne. The title compound was prepared from 2-chloro-4-trimethylsilyl-1-buten-3-yne (159 mg, 1.0 mmol) and (*E*)-1-iodo-2-bromoethylene (350 mg, 1.5 mmol). Purification by column chromatography (silica gel, hexane) afforded 188 mg (83%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.25 (s, 9 H), 6.30 (d, J = 14.0 Hz, 1 H), 6.93 (d, J = 14.0 Hz, 1 H) ppm; ^{13}C NMR ($CDCl_3$) −0.25 (3 C), 73.23, 76.58, 87.60, 92.62, 116.59, 123.26 ppm. HRMS: calculated for $C_9H_{11}BrSi$, 225.9813; found, 225.9812.

(xiii) (*E*)-1-Trimethylsilyl-8-trimethylsilyl-3-octen-1,5,7-triyne. The title compound was prepared from 2-chloro-4-trimethylsilyl-1-buten-3-yne (174 mg, 1.1 mmol) and (*E*)-1-bromo-4-trimethylsilyl-1-buten-3-yne (203 mg, 1.0 mmol). Purification by column chromatography (silica gel, hexane) afforded 210 mg (86%) of the title compound as a colorless oil: ^{1}H NMR ($CDCl_3$) 0.23 (s, 9 H), 0.25 (s, 9 H), 6.07 (d, J = 16.0 Hz, 1 H), 6.19 (d, J = 16.0 Hz, 1 H) ppm; ^{13}C NMR ($CDCl_3$) −0.20 (3 C), −0.03 (3 C), 75.12, 79.82, 87.88, 93.56, 102.89, 103.13, 120.42, 124.81 ppm. HRMS: calculated for $C_{14}H_{20}Si_2$, 244.1104; found, 244.1109.

(*E*)-1-Chloro-1-decen-3-yne.[13] Copper iodide (190 mg, 1 mmol) was added to a solution of (*E*)-1,2-dichloroethylene (9.69 g, 100 mmol), 1-octyne (2.20 g, 20 mmol), *n*-$BuNH_2$ (2.19 g, 30 mmol), and $Pd(PPh_3)_4$ (1.16 g, 1 mmol) in benzene (40 mL) at 23 °C. The reaction mixture was stirred for 5 h, and an aliquot was analyzed by GLC with mesitylene as an internal standard. Analysis indicated the formation of the title compound in 78% yield along with the dialkynylation compound found in 11% yield. The reaction mixture was hydrolyzed with aqueous ammonium chloride, extracted with Et_2O, dried over $MgSO_4$, filtered, and concentrated. Distillation gave the title compound 2.56 g (75%) as a colorless liquid: bp 83−85 °C (5 mmHg); ^{1}H NMR ($CDCl_3$) 0.92 (t, J = 6.4 Hz, 3 H), 1.3−1.6 (m, 8 H), 2.3−2.35 (m, 2 H), 5.9−5.95 (m, 1 H), 6.47 (d, J = 13.6 Hz, 1 H) ppm; ^{13}C NMR ($CDCl_3$) 14.19, 19.60, 22.78, 28.74, 28.81, 31.58, 75.91, 93.55, 114.54, 122.82 ppm.

Conversion of (*E*)-1-Chloro-1-decen-3-yne to Conjugated Diynes *via* Elimination with *n*-BuLi and Pd-Catalyzed Negishi Coupling. (a) 1-Phenyl-1,3-decadiyne (3i).[5b] **Representative Procedure.** To a solution of (*E*)-1-chloro-1-decen-3-yne (187 mg, 1.1 mmol) in 1 mL of THF (4 mL) was added *n*-BuLi (0.88 mL of 2.5 M hexane solution, 2.2 mmol) at −78 °C. The reaction mixture was stirred first at −78 °C for 30 min and then at −30 °C for 30 min, treated with a solution of anhydrous $ZnBr_2$ (270 mg, 1.2 mmol) in THF (1 mL), and warmed to 0 °C over 30 min. Iodobenzene (204 mg, 1.0 mol) and $Pd(PPh_3)_4$ (58 mg, 0.05 mmol) were added to the reaction mixture at 0 °C, which was then stirred at 23 °C for 3 h, and an aliquot was analyzed by GLC with mesitylene as an internal standard. Analysis indicated the formation of the title compound in 89% yield.

(b) Methyl (*E*)-2-Tridecen-4,6-diynoate (3iv).[5b] The title compound was prepared from (*E*)-1-chloro-1-decen-3-yne (187 mg, 1.1 mmol) and methyl (*E*)-3-bromo-2-methyl-2-propenoate (179 mg, 1.0 mmol): yield 91% by GLC.

(c) 7,9,11-Octadecatriyne. The title compound was prepared from (*E*)-1-chloro-1-decen-3-yne (187 mg, 1.1 mmol) and 1-iodo-1-octyne (236 mg, 1.0 mmol): yield, 148 mg (61%, 72% by GLC); ^{1}H NMR ($CDCl_3$) 0.91 (t, J = 6.4 Hz, 6 H), 1.3−1.6 (m, 16 H), 2.30 (t, J = 6.9 Hz, 4 H) ppm; ^{13}C NMR ($CDCl_3$) 14.27, 19.65, 22.76, 28.34, 28.77, 31.51, 60.64, 65.96, 79.59 ppm. HRMS: calculated for $C_{18}H_{26}$, 242.2035; found, 242.2028.

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