ACS OMEGA

Article

Cite This: ACS Omega 2019, 4, 19499−19504

http://pubs.acs.org/journal/acsodf

Palladium-Catalyzed Three-Component Coupling of 1,1-Dibromoalkenes, Vinylzinc Chloride, and Soft Nucleophiles: One-Pot Synthesis of 1,3-Disubstituted Allenes

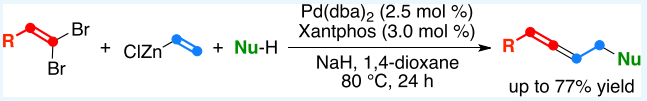
Eri Sawano[†,‡] and Masamichi Ogasawara[*,†]

[†]Department of Natural Science, Graduate School of Science and Technology and Research Cluster on "Innovative Chemical Sensing", Tokushima University, Tokushima 770-8506, Japan

[‡]Graduate School of Life Science, Hokkaido University, Kita-ku, Sapporo 001-0021, Japan

Supporting Information

ABSTRACT: The three-component coupling reaction of 1,1-dibromoalkenes **1**, vinylzinc chloride **2**, and carbon soft nucleophiles **3** was realized in the presence of the catalytic palladium/Xantphos species, and 1,3-disubstituted allenic products **5** were obtained in yields of up to 77%. The successive two palladium-catalyzed processes, namely the cross-coupling reaction and the allylic substitution, assembled **5** from the easily accessible starting compounds.

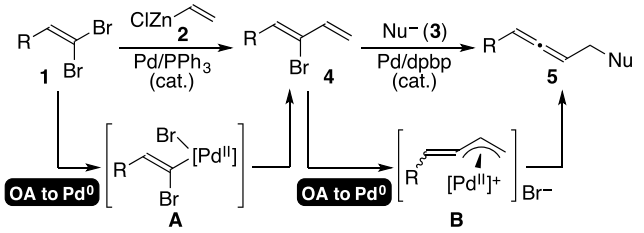


INTRODUCTION

Allenes have emerged as unique building blocks in synthetic organic chemistry,[1] and their convenient synthetic methods have been highly desirable. Construction of allenic C=C=C frameworks by multicomponent coupling reactions of easily accessible compounds is an attractive procedure for preparing allenic compounds.

In 2000, we developed a palladium-catalyzed reaction for preparing various functionalized allenes **5** starting with 1-hydrocarbyl-2-bromo-1,3-dienes **4** and appropriate soft nucleophiles **3** (Scheme 1).[2] By the use of a chiral palladium catalyst, the reaction could provide scalemic axially chiral allenes **5** in up to 94% ee.[3] The reaction proceeds via (alkylidene-π-allyl)palladium intermediate **B**,[4] that is somewhat similar to the widely accepted intermediates in the Tsuji−Trost reaction.[5] An analogous (alkylidene-π-allyl)palladium species can be generated by the addition of an allenylmethyl ester to a zero-valent palladium species and its reaction with a soft nucleophile gives a comparable allenic product as well.[6] Bromodiene substrates **4** were prepared by the regioselective cross-coupling reaction between 1,1-dibromoalkenes **1** and vinylzinc chloride **2** in the presence of catalytic $Pd(PPh_3)_4$.[2a]

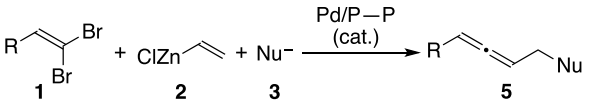
Scheme 1. Reported "Stepwise" Process of Preparing 1,3-Disubstituted Allenes Using Two Different Palladium Precatalysts



The two reaction steps shown in Scheme 1 are analogous to each other; both are palladium-catalyzed processes which involve the oxidative addition of an olefinic C−Br bond to a zero-valent palladium species, and generated palladium(II) intermediates **A** or **B** react with nucleophilic reagents subsequently (Scheme 1).

Due to the close similarity of the two palladium-catalyzed reactions, we envisioned that if we could manage both reaction steps in "one-pot" in the presence of a single palladium species starting with a mixture of three reactants **1**, **2**, and **3**, the whole reaction could be a unique three-component coupling reaction giving allenic compounds **5** by a single operation (Scheme 2).

Scheme 2. Palladium-Catalyzed Three-Component Coupling of Preparing 1,3-Disubstituted Allenes



After the extensive optimization of the reaction conditions, indeed, the three-component coupling reactions have been realized. Here, we report details of our efforts toward this goal.

RESULTS AND DISCUSSION

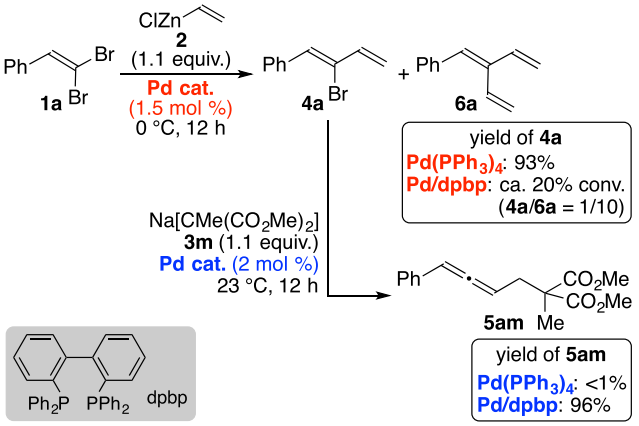
In the previous reports,[2a] the two different palladium precatalysts were employed in the respective reaction steps in Scheme 1. While $Pd(PPh_3)_4$ (1.5 mol %) was chosen as a suitable precatalyst in the regioselective cross-coupling reaction of **1** with **2**, the reaction between **3** and **4** was catalyzed by a palladium species (2.0 mol %) generated in situ from [PdCl(π-

Received: October 16, 2019
Accepted: October 29, 2019
Published: November 8, 2019

DOI: 10.1021/acsomega.9b03444
ACS Omega 2019, 4, 19499−19504

allyl)]$_2$ and 2,2′-bis(diphenylphosphino)-1,1′-biphenyl (dpbp).[7] Under the reported conditions, the two palladium species were not interconvertible. That is, the cross-coupling reaction between **1a** and **2** was much slower and much less regioselective in the presence of the Pd/dpbp species (1.5 mol %) instead of Pd(PPh$_3$)$_4$. The reaction showed ca. 20% conversion and the formation of triene **6a** was dominant under the otherwise identical conditions. Alternatively, the use of Pd(PPh$_3$)$_4$ (2.0 mol %) in the reaction between **3m** and **4a** provided the desired allenic product **5am** in less than a 1% yield (Scheme 3).

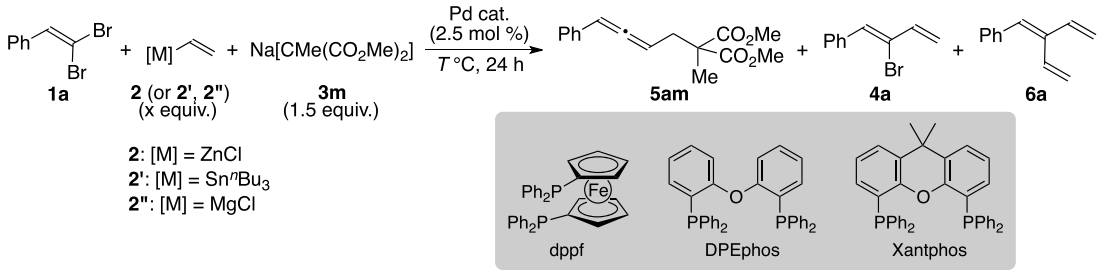
Scheme 3. Specificity of Palladium Precatalysts in Converting 1a to 5am via 4a



At the outset, a possibility of the three-component coupling was investigated for the reaction between **1a**, a vinyl nucleophile (**2**, **2′**, or **2″**), and **3m**. The results of the screening are summarized in Table 1. A treatment of **1a** with **2** (1.5 equiv) and **3m** (1.5 equiv) in the presence of a palladium species generated from [Pd(π-allyl)Cl]$_2$ and dpbp (2.5 mol %) at 60 °C in THF for 24 h gave a mixture of **1a**, **4a**, **6a**, and **5am** in 44:2:51:3 molar ratio (determined by ^{1}H NMR; entry 1). The use of vinyltin reagent **2′** instead of **2** led to complete consumption of **1a**, however, a considerable amount of uncharacterized species was formed together with **4a** and **6a**. Allene **5am** was not detected in the reaction mixture (entry 2). The reaction with vinylmagnesium chloride **2″** was very messy and the formation of **5am** was not observed (entry 3). From the results in entries 1−3, zinc reagent **2** was chosen as a vinyl nucleophile. Preformed Pd(PPh$_3$)$_4$ was slightly more effective than the Pd/dpbp species giving a mixture of **4a**, **6a**, and **5am** in 28:60:12 molar ratio. Although **1a** was completely consumed, the main product was triene **6a**, and the formation of allene **5am** was still minimal (entry 4). The Pd/dppf precatalyst[8] gave **4a** as a major product, with a small amount of **5am** (entry 5). The yield of **5am** was improved to 31% by the use of DPEphos[9] as an ancillary ligand, and the formation of **6a** was somewhat suppressed (entry 6). Reducing the amount of **2** (1.0 equiv) or lowering the reaction temperature (40 °C) did not improve the **6a**/**5m** ratios, while the reactions were slower (entries 7 and 8). Running the reaction at 80 °C in 1,4-dioxane dramatically improved the yield of **5am** to 62% (entry 9). The use of a palladium species generated from [Pd(π-allyl)Cl]$_2$ and Xantphos[9] further improved the selectivity of the reaction and **5am** was isolated in a 77% yield (entry 10). The combination of Pd(dba)$_2$ and Xantphos was equally effective for the reaction to give **5am** in a 74% isolated yield (entry 11).

Due to air-stability and easier handling of Pd(dba)$_2$, the conditions of entry 11 in Table 1 were chosen as the optimized conditions, and the reactions with various dibromoolefins **1** and nucleophiles **3** were conducted in the same way. The results of the three-component coupling are summarized in

Table 1. Optimization of Reaction Conditions for Three-Component Coupling between 1a, 2, and 3m[a]

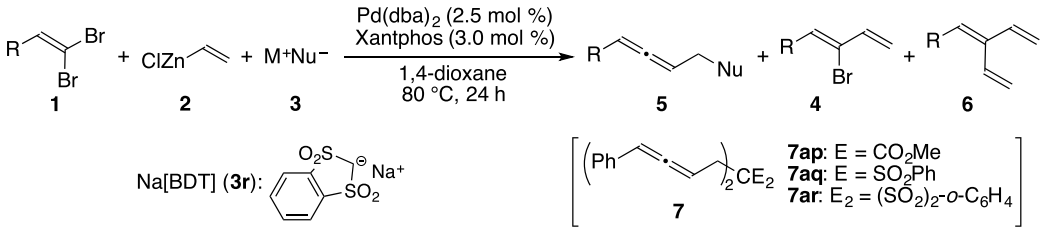


entry	Pd precursor	ligand	vinyl-[M]	x	T (°C)	solvent	**1a**/**4a**/**6a**/**5am**[b]	**5am** (%)[c]
1	[Pd(π-allyl)Cl]$_2$	dpbp	**2**	1.5	60	THF	44/2/51/3	
2	[Pd(π-allyl)Cl]$_2$	dpbp	**2′**	1.5	60	THF	0/48/52/0[d]	
3	[Pd(π-allyl)Cl]$_2$	dpbp	**2″**	1.5	60	THF	messy	
4[e]	Pd(PPh$_3$)$_4$		**2**	1.5	60	THF	0/28/60/12	
5	[Pd(π-allyl)Cl]$_2$	dppf	**2**	1.5	60	THF	1/60/31/8	
6	[Pd(π-allyl)Cl]$_2$	DPEphos	**2**	1.5	60	THF	0/51/16/33	31
7	[Pd(π-allyl)Cl]$_2$	DPEphos	**2**	1.0	60	THF	0/72/9/19	
8	[Pd(π-allyl)Cl]$_2$	DPEphos	**2**	1.5	40	THF	0/82/7/11	
9	[Pd(π-allyl)Cl]$_2$	DPEphos	**2**	1.5	80	1,4-dioxane	0/0/34/66	62
10	[Pd(π-allyl)Cl]$_2$	Xantphos	**2**	1.5	80	1,4-dioxane	0/0/10/90	77
11	Pd(dba)$_2$	Xantphos	**2**	1.5	80	1,4-dioxane	0/0/12/88	74

[a]The reaction was carried out with **1a** (0.50 mmol), **2**, and **3m** (0.75 mmol) in the presence of a palladium catalyst (2.5 mol %) generated in situ from a palladium precursor and a bisphosphine ligand. [b]Determined by the ^{1}H NMR measurement of the crude reaction mixture. [c]Isolated yield by silica gel chromatography. [d]Uncharacterized species were detected together with **4a** and **6a**. [e]Preformed tetrakis(triphenylphosphine)palladium(0) was used.

DOI: 10.1021/acsomega.9b03444
ACS Omega 2019, 4, 19499−19504

Table 2. Scope of Dibromoolefins 1 and Nucleophiles 3 in the Palladium-Catalyzed Three-Component Coupling[a]



entry	R in **1**	nucleophile **3**	**1**/**4**/**6**/**5**[b]	**5** (%)[c]
1	Ph (**1a**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	0/0/12/88	74 (**5am**)
2	4-MeO-C$_6$H$_4$ (**1b**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	0/0/22/78	64 (**5bm**)
3	4-F$_3$C-C$_6$H$_4$ (**1c**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	0/0/11/89	71 (**5cm**)
4	2,4,6-Me$_3$-C$_6$H$_2$ (**1d**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	0/0/36/64	51 (**5dm**)
5	1-naphthyl (**1e**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	0/0/32/68	63 (**5em**)
6	ferrocenyl (**1f**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	0/8/26/66	53 (**5fm**)
7	^{t}Bu (**1g**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	trace/5/5/90	62 (**5gm**)
8	Cy (**1h**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	6/38/38/18	14 (**5hm**)
9	^{n}C$_8$H$_{17}$ (**1i**)	Na[CMe(CO$_2$Me)$_2$] (**3m**)	3/37/60/0	ND
10	Ph (**1a**)	Na[CEt(CO$_2$Et)$_2$] (**3n**)	0/0/15/85	68 (**5an**)
11	Ph (**1a**)	Na[CPh(CO$_2$Et)$_2$] (**3o**)	0/0/14/86	69 (**5ao**)
12	Ph (**1a**)	Na[CH(CO$_2$Me)$_2$] (**3p**)	0/5/52/43	33 (**5ap**)
13	Ph (**1a**)	Na[CH(SO$_2$Ph)$_2$] (**3q**)	0/0/32/68	49 (**5aq**)
14	Ph (**1a**)	Na[BDT] (**3r**)	0/0/10/90	61 (**5ar**)
15	Ph (**1a**)	K[N(boc)$_2$] (**3s**)	messy	ND

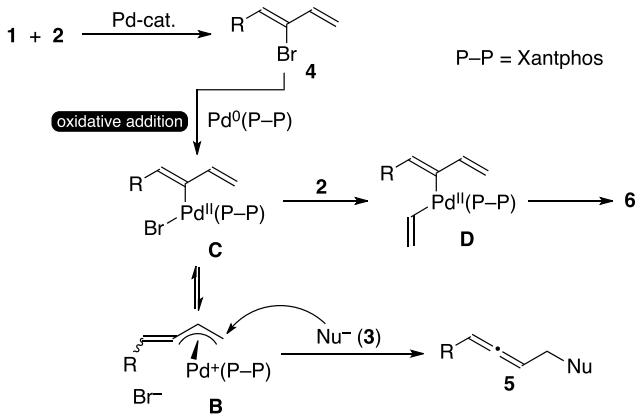
[a]The reaction was carried out with **1** (0.45−0.50 mmol), **2** (1.5 equiv to **1**), **3** (1.5 equiv to **1**), and a palladium catalyst (2.5 mol %) generated in situ from Pd(dba)$_2$ and Xantphos. [b]Determined by the ^{1}H NMR measurement of the crude reaction mixture. [c]Isolated yield by silica gel chromatography.

Table 2. The reaction works well with various 1-aryl-2,2-dibromoethylenes **1a−f** (entries 1−6). A wide range of aryl substituents, such as electron-rich (**1b**, **1d**, and **1f**), electron-poor (**1c**), bulky (**1d−f**), and organometallic (**1f**) aryl groups, can be employed in **1**, and their reactions with **2** and **3m** afforded the corresponding allenic products in good yields ranging 51−74%. On the other hand, aliphatic dibromoolefins **1g−i** showed different results in the reaction with **2** and **3m**, depending on the alkyl substituents. While substrate **1g**, which is with a bulky *tert*-butyl substituent, gave allene **5gm** in a 62% yield (entry 7), **1h** (with a *sec*-alkyl, cyclohexyl, group) provided allene **5hm** in a 14% yield (entry 8) and the reaction of **1i** (with a primary alkyl, *n*-octyl, group) did not give allenic products (entry 9). The major products in the reactions of **1h** or **1i** were the corresponding bromodienes **4** and trienes **6**.

The present protocol could be applicable to the other carbon soft nucleophiles as well. Sodium salts **3n** and **3o**, which are from ethylmalonate and phenylmalonate, reacted with **1a** in the same way to give the allenic products in 68 and 69% yields, respectively (entries 10 and 11). The reaction of **3p**, that is an anionic derivative from parent malonate, was sluggish and the yield of **5ap** was 33% (entry 12). Bis(sulphonyl)methane-derived nucleophiles, **3q** and **3r**, could be used in the present protocol affording the allenic products in 49 and 61% yields, respectively (entries 13 and 14). Allenes **5ap**, **5aq**, and **5ar** possess acidic hydrogen in them, and thus, they are capable of functioning as carbon soft nucleophiles, which may lead to the formation of bis-allenes **7** by the second three-component coupling with **1** and **2**. However, bis-allenes **7** were not detected in the ^{1}H NMR spectra nor isolated in all of the cases (entries 12−14). The reaction with nitrogen-nucleophile **3s** was messy and the desired allenic product was not obtained, although **1a** was completely consumed (entry 15). It should be mentioned that the reaction between preformed **4a** and **3s** catalyzed by Pd/dpbp gave the allenic product in an 89% yield.[2a]

Plausible reaction pathways in the present three-component coupling reaction are outlined in Scheme 4. Whereas **1a** did not react with **3m** in the absence of **2** under the optimized conditions, the initial formation of bromodiene **4** from **1** and **2** is almost certain. Indeed, a reaction of **1a** with **2** (1.0 equiv to **1a**) without **3m** under the same conditions afforded **4a**, together with unreacted **1a** and **6a** (**1a**/**4a**/**6a** = 14:77:9 molar ratio determined by the ^{1}H NMR measurement). The oxidative addition of **4** to the Pd(0) species forms **C**, which is in equilibrium with **B** with the dissociation of the bromide ligand from the palladium center.[4a] Intermediate **C** reacts with

Scheme 4. Plausible Reaction Pathways of Three-Component Coupling Reaction



DOI: 10.1021/acsomega.9b03444
ACS Omega 2019, 4, 19499−19504

2 to give triene 6, the major side-product of the present protocol, via D by the standard cross-coupling process. On the other hand, (alkylidene-π-allyl)palladium intermediate B reacts with 3, just like the Tsuji−Trost reaction, to give allene 5. Due to the wide bite-angle of Xantphos,[9] the palladium center in C is rather congested. Whereas the alkylidene-π-allyl ligand in B is much more compact[4a] than the combination of the σ-butadienyl/bromo ligands in C, the congestion at the palladium atom is somewhat diminished in B. As a consequence, Xantphos in B/C might drive the equilibrium toward B, leading to a higher yield of allene 5.

CONCLUSIONS

We have established the three-component coupling reaction of 1,1-dibromoalkenes 1, vinylzinc chloride 2, and carbon soft nucleophiles 3 leading to various 1,3-disubstituted allenes 5 in yields of up to 77%. The reaction is effectively catalyzed by the palladium/Xantphos species, and the successive two palladium-catalyzed processes, namely the cross-coupling reaction and the allylic substitution like the Tsuji−Trost reaction, assembled the allenic products in good yields from the easily accessible starting compounds.

EXPERIMENTAL SECTION

General Information. All anaerobic and/or moisture-sensitive manipulations were carried out with standard Schlenk techniques under predried nitrogen or with glove box techniques under prepurified argon. ^{1}H NMR (at 400 MHz) and ^{13}C NMR (at 101 MHz) chemical shifts are reported in ppm downfield of internal tetramethylsilane. Tetrahydrofuran and 1,4-dioxane were distilled from benzophenone-ketyl under nitrogen prior to use. $Pd(PPh_3)_4$,[10] $[Pd(\pi\text{-allyl})Cl]_2$,[11] $Pd(dba)_2$,[12] dpbp,[7] DPEphos,[9] and 1,3-benzodithiole-1,1,3,3-tetraoxide (BDT)[13] were prepared as reported. All other chemicals were obtained from commercial sources and used without additional purification.

1,1-Dibromo-1-alkenes (1a−i). These compounds were prepared from the commercially available aldehydes by the reported methods[14] and were characterized by comparison of their NMR spectra with those reported previously (**1a**,[15] **1b**,[15,16] **1c**,[15,16] **1d**,[16,17] **1e**,[16,18] **1f**,[18] **1g**,[19] **1h**,[20] and **1i**[3b]).

Palladium-Catalyzed Three-Component Coupling Reaction of 1, 2, and 3. The reaction conditions and the results are summarized in Table 2. A general procedure is given below. To a mixture of **1** (0.45−0.50 mmol), **3-H** (1.5 equiv to **1**), NaH (1.6 equiv to **1**), $Pd(dba)_2$ (2.5 mol %), and Xantphos (3.0 mol %) in 1,4-dioxane (5 mL) was added a suspension of vinylzinc chloride, which was prepared from vinylmagnesium chloride (1.4 mol/L solution in THF; 1.5 equiv to **1**) and dry $ZnCl_2$ (1.6 equiv to **1**) in 1,4-dioxane (2 mL), and the mixture was stirred for 24 h at 80 °C. The reaction mixture was filtrated through a short pad of silica gel, and the silica gel pad was washed with a small amount of Et_2O three times. The combined organic solution was evaporated to dryness under reduced pressure. The residue was chromatographed on silica gel to give allene **5** in the pure form. The characterization data of the allenic products are listed below.

Dimethyl 2-Methyl-2-(4-phenylbuta-2,3-dienyl)-propane-1,3-dioate (5am).[2a] Pale-yellow oil. Yield: 101 mg (0.37 mmol; 74%) starting with **1a** (131 mg; 0.50 mmol). This is a known compound and was characterized by a comparison of its NMR spectra with those reported previously.

Dimethyl 2-[4-(4-Methoxyphenyl)buta-2,3-dienyl]-2-methylpropane-1,3-dioate (5bm). Pale-yellow oil. Yield: 87 mg (0.29 mmol; 64%) starting with **1b** (131 mg; 0.45 mmol). ^{1}H NMR ($CDCl_3$): δ 1.51 (s, 3H), 2.68−2.71 (m, 2H), 3.70 (s, 3H), 3.72 (s, 3H), 3.80 (s, 3H), 5.42 (td, J = 7.2 and 6.4 Hz, 1H), 6.10 (dt, J = 6.4 and 2.4 Hz, 1H), 6.84 (d, J = 8.8 Hz, 2H), 7.18 (d, J = 8.8 Hz, 2H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 19.9, 35.7, 52.58, 52.61, 53.8, 55.3, 89.2, 94.0, 114.1, 126.3, 127.9, 158.7, 172.1, 172.2, 206.3. ESI-HRMS calculated for $C_{17}H_{20}O_5Na$ (M + Na): 328.1242; found: 328.1251.

Dimethyl 2-Methyl-2-[4-(4-trifluoromethylphenyl)-buta-2,3-dienyl]propane-1,3-dioate (5cm). Pale-yellow oil. Yield: 109 mg (0.32 mmol; 71%) starting with **1c** (149 mg; 0.45 mmol). ^{1}H NMR ($CDCl_3$): δ 1.51 (s, 3H), 2.73 (dd, J = 7.8 and 2.5 Hz, 2H), 3.71 (s, 3H), 3.73 (s, 3H), 5.54 (td, J = 7.8 and 6.4 Hz, 1H), 6.17 (dt, J = 6.4 and 2.5 Hz, 1H), 7.35 (d, J = 8.2 Hz, 2H), 7.54 (d, J = 8.2 Hz, 2H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 20.1, 35.5, 52.81, 52.84, 53.8, 90.2, 93.9, 123.0, 125.6 (q, J_{CF} = 3.8 Hz), 127.0, 129.0 (q, J_{CF} = 32.5 Hz), 138.3 (q, J_{CF} = 1.5 Hz), 172.13, 172.14, 207.7. ^{19}F NMR ($CDCl_3$): δ −62.3. ESI-HRMS calculated for $C_{17}H_{17}F_3O_4Na$ (M + Na): 365.0977; found: 365.0970.

Dimethyl 2-Methyl-2-[4-(2,4,6-trimethylphenyl)buta-2,3-dienyl]propane-1,3-dioate (5dm). Pale-yellow oil. Yield: 73 mg (0.23 mmol; 51%) starting with **1d** (137 mg; 0.45 mmol). ^{1}H NMR ($CDCl_3$): δ 1.46 (s, 3H), 2.25 (s, 3H), 2.30 (s, 6H), 2.66 (dt, J = 7.6 and 2.4 Hz, 2H), 3.66 (s, 3H), 3.70 (s, 3H), 5.18 (td, J = 7.6 and 6.8 Hz, 1H), 6.20 (dt, J = 6.8 and 2.4 Hz, 1H), 6.84 (s, 2H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 19.9, 20.9, 21.1, 35.6, 52.478, 52.483, 53.9, 85.9, 89.8, 128.4, 128.9, 136.19, 136.24, 172.1, 172.2, 207.7. ESI-HRMS calculated for $C_{19}H_{24}O_4Na$ (M + Na): 339.1572; found: 339.1565.

Dimethyl 2-Methyl-2-[4-(1-naphthyl)buta-2,3-dienyl]propane-1,3-dioate (5em). Pale-yellow oil. Yield: 103 mg (0.32 mmol; 63%) starting with **1e** (156 mg; 0.50 mmol). ^{1}H NMR ($CDCl_3$): δ 1.53 (s, 3H), 2.76−2.78 (m, 2H), 3.67 (s, 3H), 3.71 (s, 3H), 5.51 (td, J = 7.3 and 6.4 Hz, 1H), 6.84 (dt, J = 6.4 and 2.4 Hz, 1H), 7.42−7.54 (m, 4H), 7.73 (d, J = 8.0 Hz, 1H), 7.84 (d, J = 8.2 Hz, 1H), 8.17 (d, J = 8.0 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 20.0, 35.6, 52.57, 52.59, 53.8, 88.3, 91.0, 123.4, 125.4, 125.6, 125.7, 126.0, 127.5, 128.6, 130.3, 130.7, 133.8, 172.10, 172.12, 208.2. ESI-HRMS calculated for $C_{20}H_{20}O_4Na$ (M + Na): 347.1259; found: 347.1259.

Dimethyl 2-(4-Ferrocenylbuta-2,3-dienyl)-2-methyl-propane-1,3-dioate (5fm). Red-orange oil. Yield: 101 mg (0.26 mmol; 53%) starting with **1f** (185 mg; 0.50 mmol). ^{1}H NMR ($CDCl_3$): δ 1.51 (s, 3H), 2.58−2.70 (m, 2H), 3.72 (s, 3H), 3.74 (s, 3H), 4.11 (s, 5H), 4.15−4.17 (m, 2H), 4.20−4.24 (m, 2H), 5.15 (td, J = 7.3 and 6.4 Hz, 1H), 5.84 (dt, J = 6.4 and 2.4 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 19.9, 35.8, 52.57, 52.62, 53.8, 67.0, 67.1, 68.35, 68.36, 69.2, 80.3, 87.8, 90.8, 172.1, 172.2, 205.8. ESI-HRMS calculated for $C_{20}H_{22}FeO_4Na$ (M + Na): 405.0765; found: 407.0765.

Dimethyl 2-(5,5-Dimethyl-2,3-hexadienyl)-2-methyl-propane-1,3-dioate (5gm).[3c] Colorless oil. Yield: 79 mg (0.31 mmol; 62%) starting with **1g** (121 mg; 0.50 mmol). This is a known compound and was characterized by a comparison of its NMR spectra with those reported previously.

Dimethyl 2-(4-Cyclohexyl-2,3-butadienyl)-2-methyl-propan-1,3-dioate (5hm).[2b] Colorless oil. Yield: 20 mg

DOI: 10.1021/acsomega.9b03444
ACS Omega 2019, 4, 19499−19504

(0.071 mmol; 14%) starting with **1h** (134 mg; 0.50 mmol). This is a known compound and was characterized by a comparison of its NMR spectra with those reported previously.

Diethyl 2-Ethyl-2-(4-phenylbuta-2,3-dienyl)propane-1,3-dioate (5an). Pale-yellow oil. Yield: 107 mg (0.34 mmol; 68%) starting with **1a** (131 mg; 0.50 mmol). ^{1}H NMR ($CDCl_3$): δ 0.85 (t, J = 8.0 Hz, 3H), 1.22 (t, J = 7.2 Hz, 3H), 1.25 (t, J = 7.2 Hz, 3H), 2.05 (q, J = 8.0 Hz, 2H), 2.74 (dd, J = 8.0 and 2.4 Hz, 2H), 4.13−4.23 (m, 4H), 5.38 (td, J = 8.0 and 6.4 Hz, 1H), 6.12 (dt, J = 6.4 and 2.4 Hz, 1H), 7.17−7.20, (m, 1H), 7.25−7.31 (m, 4H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 8.5, 14.1, 14.2, 25.3, 31.8, 58.0, 61.30, 61.32, 89.3, 94.6, 126.9, 127.0, 128.6, 134.3, 171.175, 171.179, 206.8. ESI-HRMS calculated for $C_{19}H_{24}O_4$: 317.1753; found: 317.1758.

Diethyl 2-Phenyl-2-(4-phenylbuta-2,3-dienyl)-propane-1,3-dioate (5ao). Pale-yellow oil. Yield: 125 mg (0.34 mmol; 69%) starting with **1a** (131 mg; 0.50 mmol). ^{1}H NMR ($CDCl_3$): δ 1.21 (t, J = 7.2 Hz, 3H), 1.23 (t, J = 7.2 Hz, 3H), 3.15−3.18 (m, 2H), 4.17−4.30 (m, 4H), 5.50 (q, J = 7.2 Hz, 1H), 6.04 (dt, J = 6.8 and 2.4 Hz, 1H), 7.10−7.17 (m, 3H), 7.22−7.26 (m, 2H), 7.30−7.37 (m, 3H), 7.44−7.47 (m, 2H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 14.06, 14.09, 36.1, 61.85, 61.87, 62.8, 90.0, 94.6, 126.9 (2C), 127.7, 128.3 (2C), 128.6, 134.2, 136.5, 170.22, 170.24, 207.0. ESI-HRMS calculated for $C_{23}H_{25}O_4Na$ (M + H): 365.1753; found: 365.1759.

Dimethyl 2-(4-Phenylbuta-2,3-dienyl)propane-1,3-dioate (5ap).[2a] Colorless oil. Yield: 43 mg (0.165 mmol; 33%) starting with **1a** (131 mg; 0.50 mmol). This is a known compound and was characterized by comparison of its NMR spectra with those reported previously.

1-Phenyl-5,5-bis(phenylsulfonyl)penta-1,2-diene (5aq). Pale-yellow solid. Yield: 104 mg (0.245 mmol; 49%) starting with **1a** (131 mg; 0.50 mmol). ^{1}H NMR ($CDCl_3$): δ 2.93−3.08 (m, 2H), 4.65 (t, J = 5.4 Hz, 1H), 5.69 (q, J = 6.4 Hz, 1H), 6.20 (dt, J = 6.4 and 3.2 Hz, 1H), 7.22−7.26 (m, 3H), 7.30−7.34 (m, 2H), 7.46−7.50 (m, 2H), 7.53−7.57 (m, 2H), 7.63−7.70 (m, 2H), 7.85−7.89 (m, 2H), 7.94−7.97 (m, 2H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 24.7, 82.2, 91.3, 98.0, 127.0, 127.5, 128.6, 129.03, 129.05, 129.4, 129.5, 133.1, 134.5, 134.6, 137.6, 137.8, 204.8. ESI-HRMS calculated for $C_{23}H_{20}O_4S_2Na$ (M + Na): 447.0701; found: 447.0695.

2-(4-Phenylbuta-2,3-dienyl)benzodithiole 1,1,3,3-Tetraoxide (5ar). Pale-yellow solid. Yield: 106 mg (0.306 mmol; 61%) starting with **1a** (131 mg; 0.50 mmol). ^{1}H NMR ($CDCl_3$): δ 3.06−3.21 (m, 2H), 4.57 (t, J = 7.2 Hz, 1H), 5.82 (dt, J = 6.8 and 6.4 Hz, 1H), 6.41 (dt, J = 6.8 and 2.8 Hz, 1H), 7.21−7.26 (m, 1H), 7.30−7.35 (m, 4H), 7.89−7.94 (m, 2H), 7.99−8.05 (m, 2H). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 22.6, 73.0, 88.0, 98.1, 122.59, 122.61, 127.2, 127.6, 128.7, 133.0, 135.19, 135.20, 137.5, 137.6, 206.2. ESI-HRMS calculated for $C_{17}H_{14}O_4S_2Na$ (M + Na): 369.0231; found: 369.0239.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.9b03444.

^{1}H NMR spectra, ^{13}C NMR spectra, and ^{19}F NMR spectrum of allenic products **5** (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: ogasawar@tokushima-u.ac.jp.

ORCID

Masamichi Ogasawara: 0000-0002-1893-3306

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by a Grant-in-Aid for Challenging Exploratory Research (16K13989) to M.O. from JSPS, Japan. We are grateful to Dr. Yen-Chou Chen for his assistance in data collection.

■ REFERENCES

(1) (a) Krause, N., Ed. *Science of Synthesis: Houben-Weyl Methods of Molecular Transformations*; Georg Thieme Verlag: Stuttgart, 2008; *Vol. 44* (Cumulenes and Allenes). (b) Brummond, K. M.; DeForrest, J. E. Synthesizing Allenes Today (1982-2006). *Synthesis* **2007**, *2007*, 795−818. (c) Ogasawara, M. Catalytic Enantioselective Synthesis of Axially Chiral Allenes. *Tetrahedron: Asymmetry* **2009**, *20*, 259−271. (d) Yu, S.; Ma, S. How Easy Are the Syntheses of Allenes? *Chem. Commun.* **2011**, *47*, 5384−5418. (e) Yu, S.; Ma, S. Allenes in Catalytic Asymmetric Synthesis and Natural Product Syntheses. *Angew. Chem., Int. Ed.* **2012**, *51*, 3074−3112. (f) Ye, J.; Ma, S. Conquering Three-Carbon Axial Chirality of Allenes. *Org. Chem. Front.* **2014**, *1*, 1210−1224.

(2) (a) Ogasawara, M.; Ikeda, H.; Hayashi, T. π-Allylpalladium-Mediated Catalytic Synthesis of Functionalized Allenes. *Angew. Chem., Int. Ed.* **2000**, *39*, 1042−1044. (b) Ogasawara, M.; Ge, Y.; Uetake, K.; Fan, L.; Takahashi, T. Preparation of Multisubstituted Allenes from Allylsilanes. *J. Org. Chem.* **2005**, *70*, 3871−3876. (c) Ogasawara, M.; Suzuki, M.; Takahashi, T. Preparation of C_2-Symmetric Allenes by Palladium-Catalyzed Double-Nucleophilic Substitution on 3-Bromo-penta-2,4-dienyl Acetate. *J. Org. Chem.* **2012**, *77*, 5406−5410.

(3) (a) Ogasawara, M.; Ikeda, H.; Nagano, T.; Hayashi, T. Palladium-Catalyzed Asymmetric Synthesis of Axially Chiral Allenes: A Synergistic Effect of Dibenzalacetone on High Enantioselectivity. *J. Am. Chem. Soc.* **2001**, *123*, 2089−2090. (b) Ogasawara, M.; Nagano, T.; Hayashi, T. A New Route to Methyl (*R*,*E*)-(−)-Tetradeca-2,4,5-trienoate (Pheromone of Acanthoscelides obtectus) Utilizing a Palladium-Catalyzed Asymmetric Allene Formation Reaction. *J. Org. Chem.* **2005**, *70*, 5764−5767. (c) Ogasawara, M.; Ngo, H. L.; Sakamoto, T.; Takahashi, T.; Lin, W. Applications of 4,4'-$(Me_3Si)_2$-BINAP in Transition-Metal-Catalyzed Asymmetric Carbon-Carbon Bond-Forming Reactions. *Org. Lett.* **2005**, *7*, 2881−2884. (d) Ogasawara, M.; Okada, A.; Subbarayan, V.; Sörgel, S.; Takahashi, T. Palladium-Catalyzed Asymmetric Synthesis of Axially Chiral Allenylsilanes and Their Application to S_E2' Chirality Transfer Reactions. *Org. Lett.* **2010**, *12*, 5736−5739.

(4) (a) Ogasawara, M.; Okada, A.; Watanabe, S.; Fan, L.; Uetake, K.; Nakajima, K.; Takahashi, T. Synthesis, Structure, and Reactivity of (1,2,3-η^3-Butadien-3-yl)palladium Complexes. *Organometallics* **2007**, *26*, 5025−5029. (b) Zeng, X.; Hu, Q.; Qian, M.; Negishi, E. Clean Inversion of Configuration in the Pd-Catalyzed Cross-Coupling of 2-Bromo-1,3-dienes. *J. Am. Chem. Soc.* **2003**, *125*, 13636−13637.

(5) (a) Tsuji, J. Carbon-Carbon Bond Formation via Palladium Complexes. *Acc. Chem. Res.* **1969**, *2*, 144−152. (b) Trost, B. M.; Van Vranken, D. L. Asymmetric Transition Metal-Catalyzed Allylic Alkylations. *Chem. Rev.* **1996**, *96*, 395−422. (c) Trost, B. M.; Chulbom, L. Asymmetric Allylic Alkylation Reaction. In *Catalytic Asymmetric Synthesis*, 2nd ed.; Ojima, I., Ed.; VCH: New York, 2000; pp 593−649. (d) Consiglio, G.; Waymouth, M. Enantioselective Homogeneous Catalysis Involving Transition-Metal-Allyl Intermediates. *Chem. Rev.* **1989**, *89*, 257−276.

DOI: 10.1021/acsomega.9b03444
ACS Omega 2019, 4, 19499−19504

(6) (a) Djahanbini, D.; Cazes, B.; Goré, J. Reactive D'esters α-Alleniques. Synthese Regiospecifique de Diesters γ-Alleniques et de Dienes−1,3. *Tetrahedron Lett.* **1984**, *25*, 203−206. (b) Trost, B. M.; Tour, J. M. Synthesis of 4-(Dimethylphenylsilyl)buta-2,3-dien-1-ol and Its Use in Alkylation. *J. Org. Chem.* **1989**, *54*, 484−486. (c) Imada, Y.; Ueno, K.; Kutsuwa, K.; Murahashi, S. Palladium-Catalyzed Asymmetric Alkylation of 2,3-Alkadienyl Phosphates. Synthesis of Optically Active 2-(2,3-Alkadienyl)malonates. *Chem. Lett.* **2002**, *31*, 140−141. (d) Trost, B. M.; Fandrick, D. R.; Dinh, D. C. Dynamic Kinetic Asymmetric Allylic Alkylations of Allenes. *J. Am. Chem. Soc.* **2005**, *127*, 14186−14187. (e) Wan, B.; Ma, S. Enantioselective Decarboxylative Amination: Synthesis of Axially Chiral Allenyl Amines. *Angew. Chem., Int. Ed.* **2013**, *52*, 441−445.

(7) Ogasawara, M.; Yoshida, K.; Hayashi, T. 2,2'-Bis-(diphenylphosphino)-1,1'-biphenyl: New Entry of Bidentate Triarylphosphine Ligand to Transition Metal Catalysts. *Organometallics* **2000**, *19*, 1567−1571.

(8) Hayashi, T.; Konishi, M.; Kobori, Y.; Kumada, M.; Higuchi, T.; Hirotsu, K. Dichloro[1,1'-bis(diphenylphosphino)ferrocene]-palladium(II): an Effective Catalyst for Cross-Coupling of Secondary and Primary Alkyl Grignard and Alkylzinc Reagents with Organic Halides. *J. Am. Chem. Soc.* **1984**, *106*, 158−163.

(9) Kranenburg, M.; van der Burgt, Y. E. M.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Goubitz, K.; Fraanje, J. New Diphosphine Ligands Based on Heterocyclic Aromatics Inducing Very High Regioselectivity in Rhodium-Catalyzed Hydroformylation: Effect of the Bite Angle. *Organometallics* **1995**, *14*, 3081−3089.

(10) Coulson, D. R. Tetrakis(triphenylphosphine)palladium(0). *Inorg. Synth.* **1972**, *13*, 121−124.

(11) Tatsuno, Y.; Yoshida, T.; Otsuka, S. (η^3-Allyl)Palladium(II) Complexes. *Inorg. Synth.* **1979**, *19*, 220−223.

(12) Ukai, T.; Kawazura, H.; Ishii, Y.; Bonnet, J. J.; Ibers, J. A. Chemistry of Dibenzylideneacetone-Palladium(0) complexes: I. Novel Tris(dibenzylideneacetone)dipalladium(solvent) Complexes and Their Reactions with Quinones. *J. Organomet. Chem.* **1974**, *65*, 253−266.

(13) Kündig, E. P.; Cunningham, A. F., Jr. 1,3-Benzodithiole Tetraoxide as a CH_2^{2-} Synthon. *Tetrahedron* **1988**, *44*, 6855−6860.

(14) (a) Ramirez, F.; Desai, N. B.; McKelvie, N. A New Synthesis of 1,1-Dibromoölefins via Phosphine-Dibromomethylenes. The Reaction of Triphenylphosphine with Carbon Tetrabromide. *J. Am. Chem. Soc.* **1962**, *84*, 1745−1747. (b) Corey, E. J.; Fuchs, P. L. A Synthetic Method for Formyl → Ethynyl Conversion (RCHO → RC≡CH or RC≡CR'). *Tetrahedron Lett.* **1972**, *13*, 3769−3772.

(15) Huh, D. H.; Jeong, J. S.; Lee, H. B.; Ryu, H.; Kim, Y. G. An Efficient Method for One-Carbon Elongation of Aryl Aldehydes via Their Dibromoalkene Derivatives. *Tetrahedron* **2002**, *58*, 9925−9932.

(16) Ma, X.; Herzon, S. B. Synthesis of Ketones and Esters from Heteroatom-Functionalized Alkenes by Cobalt-Mediated Hydrogen Atom Transfer. *J. Org. Chem.* **2016**, *81*, 8673−8695.

(17) Theunissen, C.; Métayer, B.; Henry, N.; Compain, G.; Marrot, J.; Martin-Mingot, A.; Thibaudeau, S.; Evano, G. Keteniminium Ion-Initiated Cascade Cationic Polycyclization. *J. Am. Chem. Soc.* **2014**, *136*, 12528−12531.

(18) Morri, A. K.; Thummala, Y.; Doddi, V. R. The Dual Role of 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) in the Synthesis of Terminal Aryl- and Styryl-Acetylenes via Umpolung Reactivity. *Org. Lett.* **2015**, *17*, 4640−4643.

(19) Fukudome, Y.; Naito, H.; Hata, T.; Urabe, H. Copper-Catalyzed 1,2-Double Amination of 1-Halo-1-alkynes. Concise Synthesis of Protected Tetrahydropyrazines and Related Heterocyclic Compounds. *J. Am. Chem. Soc.* **2008**, *130*, 1820−1821.

(20) Rao, M. L. N.; Jadhav, D. N.; Dasgupta, P. Pd-Catalyzed Domino Synthesis of Internal Alkynes Using Triarylbismuths as Multicoupling Organometallic Nucleophiles. *Org. Lett.* **2010**, *12*, 2048−2051.

DOI: 10.1021/acsomega.9b03444
ACS Omega 2019, 4, 19499−19504