EurJOC
European Journal of Organic Chemistry

A Journal of
ChemPubSoc Europe

Accepted Article

Title: Hydrazone-Cu-catalyzed Suzuki-Miyaura-type Reaction of Dibromoalkene with Arylboronic Acid

Authors: Kohei Watanabe, Takashi Mino, Chikako Hatta, Eri Ishikawa, Yasushi Yoshida, and Masami Sakamoto

To be cited as: *Eur. J. Org. Chem.* 10.1002/ejoc.201700535

Link to VoR: http://dx.doi.org/10.1002/ejoc.201700535

Supported by
ACES Asian Chemical Editorial Society

WILEY-VCH

10.1002/ejoc.201700535

WILEY-VCH

FULL PAPER

Hydrazone-Cu-catalyzed Suzuki-Miyaura-type Reaction of Dibromoalkene with Arylboronic Acid

Kohei Watanabe,[a] Takashi Mino,*[a],[b] Chikako Hatta,[a] Eri Ishikawa,[a] Yasushi Yoshida,[a],[b] and Masami Sakamoto[a],[b]

Abstract: We found that a Suzuki-Miyaura-type reaction of dibromoalkenes with arylboronic acids using a hydrazone-Cu catalyst system proceeded smoothly under mild conditions to afford the corresponding internal alkyne derivatives in good yields. Furthermore, we succeeded in synthesis of *o*-allyloxyethynylbenzene derivatives, which are known as effective precursors of various heterocyclic compounds, *via* this reaction.

Introduction

Internal alkyne structure is one of the most important compounds in organic synthetic chemistry because this is a common structure in useful and versatile synthetic intermediates.[1] Recently, various intramolecular reactions of internal alkyne derivatives were reported.[2] Therefore, development of a synthetic methodology of internal alkyne derivatives has possibilities to contribute to the development of organic synthesis, and is strongly desired.

Pd/Cu-catalyzed Sonogashira coupling reaction of arylhalides with terminal alkynes is a well-known first choice for the preparation of internal alkyne structures.[3] Recently, Sonogashira coupling reactions using only common metal catalysts such as Cu-,[4] Ni-[5] and Fe-catalyst[6] instead of precious metal catalyst were reported. Although these reactions were attractive because common metals are less toxic and exist abundantly on the earth compared with precious metal, all reactions required high temperature except for one.[4k] Therefore, the preparation of internal alkyne structures using common metal catalyst remains challenging.

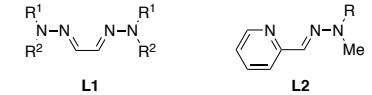
On the other hand, Pd-catalyzed Suzuki-Miyaura-type reactions of bromoalkynes with aryl boronic acids for the construction of internal alkyne structure were reported as an alternative method of Sonogashira reaction.[7] The Wang group[7b] and Tang group[7c] reported that this reaction proceeded even under room temperature in the presence of Pd-catalyst. In 2011, the Wang group reported that this reaction using Cu-catalyst proceeded and gave internal alkyne derivatives.[8] However, this reaction also required reflux conditions.

[a] Graduate School of Engineering, Chiba University,
1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
E-mail: tmino@faculty.chiba-u.jp
http://chem.tf.chiba-u.jp/gacb06/index.html
[b] Molecular Chirality Research Center, Chiba University,
1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

Supporting information for this article is given via a link at the end of the document.

As a further protocol for the preparation of internal alkyne structure, one-pot reaction of Pd-catalyzed Suzuki-Miyaura-type reaction of dibromoalkenes instead of bromoalkynes followed by dehydrobromination in the presence of strong base was reported by the Chelucci group.[9] Moreover, Pd-catalyzed cascade reactions of C-C coupling reaction and dehydrobromination using dibromoalkenes with various organometalic reagents as coupling partners were also reported.[10] First, the Shen group reported that Pd-catalyzed Stille coupling reaction of dibromoalkenes with organostannanes afforded internal alkyne derivatives.[10a] Second, the Rao group reported that Pd-catalyzed cascade reaction of dibromoalkenes with triarylbismuth produced internal alkyne derivatives.[10b] Finally, the Schmidt group reported a cascade reaction for the preparation of internal alkynes from dibromoalkenes *via* sequential Pd-catalyzed Suzuki-Miyaura-type reaction and dehydrobromination.[10c] These reactions required precious metal as a catalyst, although these are more efficient and stronger synthetic strategies for the construction of internal alkyne structure compared with the reaction using bromoalkyne as starting material because dibromoalkenes are precursors of bromoalkynes and easily prepared from readily available aldehydes *via* Corey-Fuchs reaction.[11] On another front, the Tan group[12a] and Mao group[12b] reported that Cu-catalyzed Suzuki-Miyaura-type reaction of dibromoalkenes with aryl boronic acids also afforded the internal alkyne derivatives. However, both reactions required high temperature exceeding 100 °C and high loading Cu-catalyst exceeding 10 mol%.

On the other hand, we previously demonstrated phosphine-free hydrazone compounds (Figure 1) as effective ligands for Pd-catalyzed C-C bond formations such as the Suzuki-Miyaura,[13] Mizoroki-Heck,[14] Sonogashira[15] and Hiyama[15] cross-coupling reaction of aryl halides. We also demonstrated that a hydrazone-Cu-catalyst system was effective for C-C,[16] C-O,[16] and C-N[17] bond formations. Moreover, we recently found that Suzuki-Miyaura-type reaction of bromoalkynes for internal alkyne structures proceeded even at room temperature in the presence of a hydrazone-Cu-catalyst system.[18]



L1

a: R^1 = 2-Pyridyl, R^2 = Me
b: R^1 = Ph, R^2 = Me
c: R^1, R^2 = -$(CH_2)_4$-
d: R^1, R^2 = -$(CH_2)_5$-
e: R^1, R^2 = -$(CH_2)_6$-

L2

a: R = 2-Pyridyl
b: R = Ph

Figure 1. Hydrazones **L1** and **L2**

WILEY-VCH

FULL PAPER

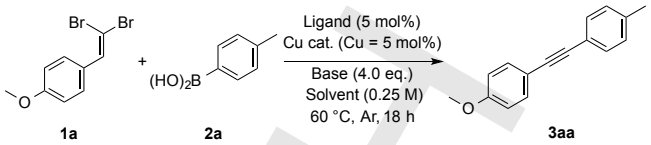
Herein, we describe a hydrazone-Cu-catalyzed Suzuki-Miyaura-type reaction of dibromoalkenes with arylboronic acids proceeded smoothly under mild conditions and afforded the corresponding internal alkyne derivatives.

Results and Discussion

Initially, we explored the optimizing reaction conditions for the Cu-catalyzed Suzuki-Miyaura-type reaction using 4-(2,2-diboromovinyl)-1-methoxybenzene (**1a**) and *p*-tolylboronic acid (**2a**) as model substrates (Table 1). Using 5 mol% of CuI and bishydrazone **L1a** as a ligand, we found that the reaction with K_3PO_4 as a base in EtOH as solvent at 60 °C gave the corresponding internal alkyne product of 1-methoxy-4-(*p*-tolylethynyl)benzene (**3aa**) in a 90% yield (Entry 1). We tested various bishydrazone ligands **L1b-e** (Entries 2-5). The reaction using a phenyl-methyl-type bishydrazone ligand **L1b** afforded the corresponding product **3aa** in 60% yield with recovery of starting material **1a** (Entry 2). When we used bishydrazone ligands **L1c-e** bearing 5-7 member rings, the desired product **3aa** was obtained in 92%, 83% and 58% yields, respectively (Entries 3-5). In particular, bishydrazone ligand **L1c** with 5 member rings is the most effective for this reaction (Entry 3). We also tested pyridine-type monohydrazone ligands **L2a** and **L2b** (Entries 6 and 7). While the reaction using the pyridine-methyl-type bishydrazone ligand **L2a** afforded a moderate yield of the corresponding product **3aa** (Entry 6), the reaction using **L2b** afforded a good yield of **3aa** (Entry 7). On the other hand, phosphine ligand such as PPh_3 was not effective for this reaction (Entry 8). Next, we investigated the effect of the Cu-catalyst (Entries 3 and 9-13). We found that CuBr, CuCl, $CuBr_2$ and $Cu(OAc)_2$ were also effective for this reaction and led to good yields of product, respectively (Entries 9-12). On the other hand, the reaction using Cu_2O afforded the corresponding product in low yield (Entry 13). Various bases were tested (Entries 3 and 14-20). While K_3PO_4 was effective for this reaction (Entry 3), the reaction using Na_3PO_4 afforded only a trace amount of product with recovery of **1a** (Entry 14). Other potassium salts such as KOAc, KF and K_2CO_3 were not effective for this reaction (Entries 15-17). The reactions in the presence of Cs_2CO_3 or $Ca(OH)_2$ afforded only a trace amount of the corresponding product (Entries 18 and 19). Amine base such as Et_3N was also not effective for this reaction (Entry 20). Next, the effects of solvent were investigated (Entries 3 and 21-29). First, we tried to use various protic solvents (Entries 3 and 21-23). We found that EtOH was the most suitable for this reaction (Entry 3). We also tested aprotic solvents (Entries 24-29). Although the reaction in MeCN afforded the corresponding product in relatively good yield (Entry 24), the reaction using other solvents gave low yields or a trace amount of product (Entries 25-29).

Optimizing reaction conditions in hand (Table 1, Entry 3), we tried to investigate the scope and limitation of this reaction by using various dibromoalkenes **1** and arylboronic acids **2** (Table 2). We found that 3- and 2-substituted (2,2-dibromovinyl)benzenes **1b** and **1c** were also tolerated and afforded the corresponding products in 77% and 66% yield, respectively (Entries 2 and 3). The reactions using electron-rich dibromoalkenes **1d** and **1e** bearing a methyl group and *tert*-butyl group with 4-methoxyphenylboronic acid (**2b**) also proceeded and gave the coupling products in moderate yields (Entries 4 and 5). The reactions using electron-poor dibromoalkenes **1f** and **1g** led to moderate yields of coupling products (Entries 6 and 7). The reaction of 2-(2,2-dibromovinyl)naphthalene (**1h**) with *p*-tolylboronic acid (**2a**) proceeded and afforded (*p*-tolylethynyl)naphthalene (**3ha**) in 81% yield (Entry 8). 1-(2,2-Dibromovinyl)-2-(methoxymethoxy)benzene (**1i**) was allowed to react with *p*-tolylboronic acid (**2a**) to produce internal alkyne derivative **3ia** in 73% yield (Entry 9). When we tested 3- and 2-substituted arylboronic acids **2c** and **2d**, both reactions also proceeded (Entries 10 and 11). Phenylboronic acid (**2e**), which has no substituent, was also tolerated in this reaction (Entry 12). The reaction using arylboronic acids **2f** and **2g** with halogen atoms such as chloro and bromo gave the corresponding products in moderate yields. (Entries 13 and 14). In the case of using electron-deficient arylboronic acid **2h**, we obtained the desired product in 44% yield (Entry 15). 2-Thienylboronic acid (**2i**)

Table 1. Optimization of reaction conditions



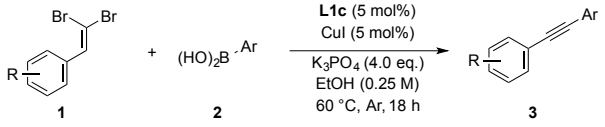
1a 2a 3aa

Entry	Ligand	Catalyst	Base	Solvent	Yield of **3aa** (%)[a]
1	**L1a**	CuI	K_3PO_4	EtOH	90
2	**L1b**	CuI	K_3PO_4	EtOH	60
3	***L1c***	***CuI***	***K_3PO_4***	***EtOH***	***92***
4	**L1d**	CuI	K_3PO_4	EtOH	83
5	**L1e**	CuI	K_3PO_4	EtOH	58
6	**L2a**	CuI	K_3PO_4	EtOH	73
7	**L2b**	CuI	K_3PO_4	EtOH	84
8	PPh_3 (10 mol%)	CuI	K_3PO_4	EtOH	17
9	**L1c**	CuBr	K_3PO_4	EtOH	80
10	**L1c**	CuCl	K_3PO_4	EtOH	85
11	**L1c**	$CuBr_2$	K_3PO_4	EtOH	82
12	**L1c**	$Cu(OAc)_2$	K_3PO_4	EtOH	79
13	**L1c**	Cu_2O	K_3PO_4	EtOH	26
14	**L1c**	CuI	Na_3PO_4	EtOH	trace
15	**L1c**	CuI	KOAc	EtOH	trace
16	**L1c**	CuI	KF	EtOH	12
17	**L1c**	CuI	K_2CO_3	EtOH	26
18	**L1c**	CuI	Cs_2CO_3	EtOH	trace
19	**L1c**	CuI	$Ca(OH)_2$	EtOH	trace
20	**L1c**	CuI	Et_3N	EtOH	trace
21	**L1c**	CuI	K_3PO_4	MeOH	39
22	**L1c**	CuI	K_3PO_4	^{i}PrOH	37
23	**L1c**	CuI	K_3PO_4	^{n}PrOH	46
24	**L1c**	CuI	K_3PO_4	MeCN	73
25	**L1c**	CuI	K_3PO_4	DMSO	33
26	**L1c**	CuI	K_3PO_4	NMP	24
27	**L1c**	CuI	K_3PO_4	DMF	trace
28	**L1c**	CuI	K_3PO_4	THF	trace
29	**L1c**	CuI	K_3PO_4	Toluene	6

[a] Isolated yield.

was also tolerated and gave 2-((*p*-methoxyphenyl)ethynyl)thiophene (**3ai**) (Entry 16). In the case of the reaction of 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) with 2-hydroxyphenylboronic acid (**2j**), the internal alkyne product of 2-((4-methoxyphenyl)ethynyl)phenol was not detected. Alternatively, we obtained 10% yield of 2-(4-methoxyphenyl)benzofuran,[19] which was formed by annulation of internal alkyne product in the presence of a large amount of base (Entry 17). The reaction of 1-(2,2-dibromovinyl)-2-(methoxymethoxy)benzene (**1i**) with 2-bromophenylboronic acid (**2k**) gave bromoalkyne derivative **1i'** in 63% yield without coupling reaction (Entry 18).

Table 2. Scope and limitation

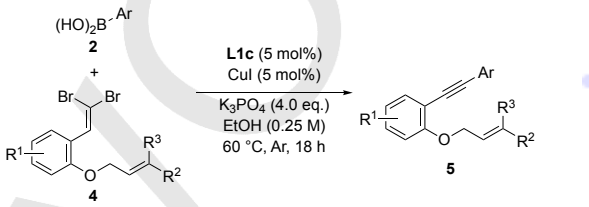


Entry	R (**1**)	Ar (**2**)	Yield of **3** (%)[a]
1	4-OMe (**1a**)	4-MeC_6H_4 (**2a**)	92 (**3aa**)
2	3-OMe (**1b**)	4-MeC_6H_4 (**2a**)	77 (**3ba**)
3	2-OMe (**1c**)	4-MeC_6H_4 (**2a**)	66 (**3ca**)
4	4-Me (**1d**)	4-$MeOC_6H_4$ (**2b**)	54 (**3db**)
5	4-^{t}Bu (**1e**)	4-$MeOC_6H_4$ (**2b**)	64 (**3eb**)
6	4-Cl (**1f**)	4-$MeOC_6H_4$ (**2b**)	59 (**3fb**)
7	4-CF_3 (**1g**)	4-$MeOC_6H_4$ (**2b**)	65 (**3gb**)
8	3,4-$(CH)_2$- (**1h**)	4-MeC_6H_4 (**2a**)	81 (**3ha**)
9	2-OMOM (**1i**)	4-MeC_6H_4 (**2a**)	73 (**3ia**)
10	4-OMe (**1a**)	3-MeC_6H_4 (**2c**)	88 (**3ac**)
11	4-OMe (**1a**)	2-MeC_6H_4 (**2d**)	64 (**3ad**)
12	4-OMe (**1a**)	Ph (**2e**)	60 (**3ae**)
13	4-OMe (**1a**)	4-ClC_6H_4 (**2f**)	65 (**3af**)
14	4-OMe (**1a**)	4-BrC_6H_4 (**2g**)	54 (**3ag**)
15	4-OMe (**1a**)	4-$CF_3C_6H_4$ (**2h**)	44 (**3ah**)
16	4-OMe (**1a**)	2-Thiophen (**2i**)	27 (**3ai**)
17[b]	4-OMe (**1a**)	2-HOC_6H_4 (**2j**)	N.D.[c]
18	2-OMOM (**1i**)	2-BrC_6H_4 (**2k**)	N.D.[d]

[α] Isolated yield. [b] This reaction was carried out at 80 °C. [c] 2-(4-Methoxyphenyl)benzofuran was obtained in 10% yield instead of internal alkyne derivative. [d] 1-(Bromoethynyl)-2-(methoxymethoxy)benzene **1i'** was obtained in 63% instead of internal alkyne derivative.

Next, we aimed to prepare *o*-allyloxyethynylbenzene derivatives which are known as useful precursors for the various oxygen-containing heterocyclic compounds.[20] Recently, we reported effective preparation of *o*-allyloxyethynylbenzene derivatives *via* Cu-catalyzed Suzuki-Miyaura-type reaction of *o*-allyloxy(bromoethynyl)benzenes.[18] In this stage, we tried to apply 1-allyloxy-2-(2,2-dibromovinyl)benzene derivatives **4** as a starting material to this reaction for the preparation of *o*-allyloxyethynylbenzene derivatives (**5**) (Table 3). We found that the reaction of 1-allyloxy-(2,2-dibromovinyl)benzene (**4a**) with *p*-tolylboronic acid (**2a**) also proceeded under the optimized reaction conditions (**Table 1**, Entry 3) and provided 1-allyloxy-2-(*p*-tolylethynyl)benzene (**5a**) in 75% yield (Entry 1). Next, we tested dibromovinylbenzenes **4b**, **4c** and **4d** bearing various substituents and obtained **5b**, **5c** and **5d** in 83%, 74% and 78% yields, respectively (Entries 2-4). Furthermore, cinnamyloxy compound **4e** and prenyloxy compound **4f** were also tolerated in this reaction and afforded the corresponding products **5e** and **5f** in good yields (Entries 5 and 6). The reaction of allyloxy compound **4a** with phenylboronic acid (**2e**) also proceeded (Entry 7). From these results, this reaction has potential to become a more efficient protocol for *o*-allyloxyethynylbenzene derivatives than Cu-catalyzed Suzuki-Miyaura-type reaction of *o*-allyloxy(bromoethynyl)benzenes.

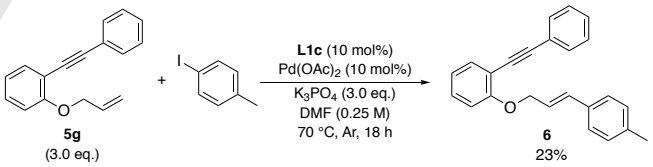
Table 3. Preparation of *o*-allyloxyethynylbenzene derivatives



Entry	Ar (**2**)	R^1	R^2	R^3 (**4**)	Yield of (**5**) (%)[a]
1	4-MeC_6H_4 (**2a**)	H	H	H (**4a**)	75 (**5a**)
2	4-MeC_6H_4 (**2a**)	4-Cl	H	H (**4b**)	83 (**5b**)
3	4-MeC_6H_4 (**2a**)	4-Me	H	H (**4c**)	74 (**5c**)
4	4-MeC_6H_4 (**2a**)	4-OMe	H	H (**4d**)	78 (**5d**)
5	4-MeC_6H_4 (**2a**)	H	Ph	H (**4e**)	80 (**5e**)
6	4-MeC_6H_4 (**2a**)	H	Me	Me (**4f**)	86 (**5f**)
7	Ph (**2e**)	H	H	H (**4a**)	75 (**5g**)

[a] Isolated yield.

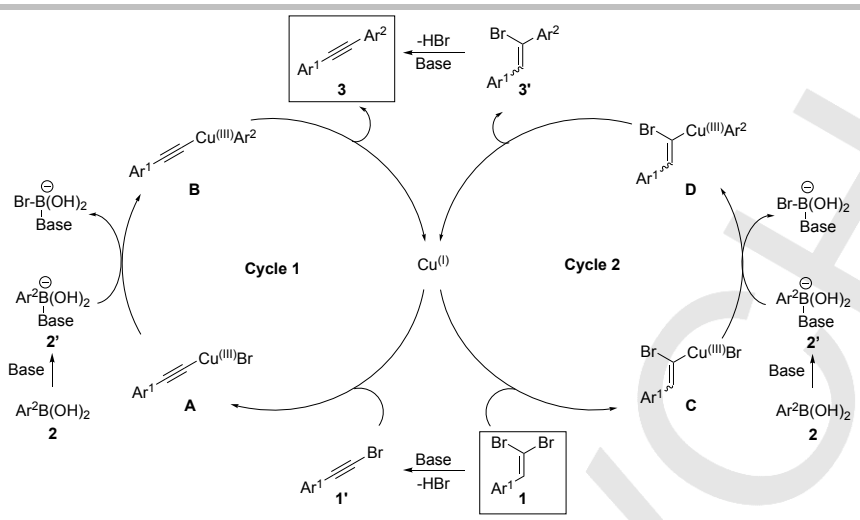
On the other hand, we previously reported that Pd-catalyzed Heck-type reaction of allylic aryl ether with aryl halides afforded cinnamyl aryl ether product.[14b] For the preparation of various *o*-cinnamyloxyethynylbenzene derivatives, we tried a Heck-type reaction of *o*-allyloxy(phenylethynyl)benzene (**5g**) with *p*-iodetoluene using a **L1c**-$Pd(OAc)_2$ catalyst system (Scheme 1).



Scheme 1. Heck-type reaction of *o*-allyloxyethynylbenzene (**5g**)

As a result, we succeeded in installing an aryl group at the end of an allyloxy moiety by Pd-catalyzed Heck-type reaction and in obtaining *o*-cinnamyloxyethynylbenzene derivative **6**.

Finally, two conceivable mechanisms of a Suzuki-Miyaura-type coupling reaction were illustrated in Scheme 2. As the first reaction mechanism (Cycle 1), the catalytic cycle that was initiated after dehydrobromination from dibromoalkene **1** by base afforded bromoalkyne **1'**. Next, oxidative addition of Cu(I) catalyst to bromoalkyne **1'** occurred and formed alkynyl-bromo-Cu(III) complex **A**. On the other hand, arylboronic acid **2** was transformed into complex **2'** by base. Next, complex **2'** underwent transmetalation with Cu(III) complex **A** to generate alkynyl-aryl-Cu(III) complex **B** followed by reductive elimination of Cu(III) complex **B**; this afforded the corresponding internal alkyne derivative and regenerated Cu(I), and the catalytic cycle was



Scheme 2. Plausible reaction mechanism

completed. This catalytic cycle was supported by the result of the reaction affording bromoalkyne intermediate **1i'** (Table 2, Entry 18). As a second conceivable reaction mechanism (Cycle 2), the catalytic cycle was initiated by oxidative addition of Cu(I) to dibromoalkene **1** directly to afford alkenyl-bromo-Cu(III) complex **C**, followed by transmetalation with complex **2'** forming alkenyl-aryl-Cu(III) **D**. Next, reductive elimination of Cu(III) complex **D** produced internal alkene intermediate **3'**. Finally, dehydrobromination of intermediate occurred by base to afford the corresponding internal alkyne **3**. This catalytic cycle was also supported by the result of the reaction using 2-hydroxyphenylboronic acid (**2j**) (Table 2, Entry 17). In this reaction, we observed ion peak at *m/z* = 304, which was derived from internal alkene intermediate **3ik'** of 2-(1-bromo-2-(4-methoxyphenyl)vinyl)phenol, on GC-MS analysis. Therefore, it is conceivable that two catalytic cycles competed with each other in this reaction.

Conclusions

In summary, we found that hydrazone-Cu-catalyzed Suzuki-Miyaura-type reaction of (2,2-dibromovinyl)benzene derivatives **1** with arylboronic acids **2** proceeded smoothly at 60 °C using 5 mol% of Cu-catalyst and afforded the corresponding internal alkyne products **3** in good yields. Furthermore, we demonstrated that this reaction has potential to become an efficient protocol for the preparation of *o*-allyloxyethynylbenzene derivatives **5**, which are known as useful precursors for various heterocyclic compounds.

Experimental Section

General: Melting points were measured with a melting point instru-ment. ^{1}H and ^{13}C NMR spectra were recorded with a 300 MHz NMR spectrometers. Chemical shifts are given in ppm downfield from TMS with chloroform as an internal standard. HRMS(ESI or APCI) data were recorded with an Orbitrap mass spectro-meter. Unless otherwise noted, all reagents were used without fur-ther purification.

General procedure for Cu-catalyzed Suzuki-Miyaura-type coupling reaction of dibromoalkenes with arylboronic acids (Tables 2 and 3)

A mixture of (2,2-dibromovinyl)bromoalkene derivatives **1** or **4** (0.25 mmol), arylboronic acids **2** (0.50 mmol), K_3PO_4 (1.0 mmol), CuI (12.5 μmol, 5 mol %) and ligand **L1c** (12.5 μmol, 5 mol %) in EtOH (1.0 mL) at 60 °C under an Ar atmosphere was stirred. After 18 h, the reaction was quenched with distilled water. The solution was extracted with ethyl acetate, washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was purified by silica gel chromatography (hexane, hexane/ethyl acetate (v/v = 250-40/1) or hexane/diethylether (v/v = 40/1)) to afford the corresponding internal alkyne products **3** or **5**.

1-Methoxy-4-(*p*-tolylethynyl)benzene (3aa)[18] (Table 1, Entry 3). Compound **3aa** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.5 mg) and *p*-tolylboronic acid (**2a**) (68.0 mg) according to the general procedure in 92% yield (50.8 mg, 0.229 mmol) as a white solid: m.p. 125-126 °C; ^{1}H NMR (300 MHz $CDCl_3$): δ = 7.46 (dt, *J* = 8.9, 2.8 Hz, 2H), 7.41 (d, *J* = 8.1 Hz, 2H), 7.14 (d, *J* = 7.9 Hz, 2H), 6.87 (dt, *J* = 8.9, 2.8 Hz, 2H), 3.82 (s, 3H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.4, 138.0, 132.9, 131.3, 129.1, 120.5, 115.6, 113.9, 88.6, 88.2, 55.3, 21.5 ppm; EI-MS *m/z* (rel intensity) 222 (M^+, 100).

1-Methoxy-3-(*p*-tolylethynyl)benzene (3ba)[18] (Table 2, Entry 2). Compound **3ba** was obtained from 1-(2,2-dibromovinyl)-3-methoxybenzene (**1b**) (72.7 mg) and *p*-tolylboronic acid (**2a**) (68.0 mg) according to the general procedure in 77% yield (42.9 mg, 0.193 mmol) as a white solid: m.p. 63-64 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.43 (d, *J* = 8.1 Hz, 2H), 7.24 (t, *J* = 7.7 Hz, 1H), 7.14 (t, *J* = 7.9 Hz, 3H), 7.06-7.05 (m, 1H), 6.90-6.86 (m, 1H), 3.81 (s, 3H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.3, 138.4, 131.5, 129.3, 129.1, 124.4, 124.1, 120.0, 116.2, 114.8, 89.4, 88.6, 55.2, 21.5 ppm; EI-MS *m/z* (rel intensity) 222 (M^+, 100).

1-Methoxy-2-(*p*-tolylethynyl)benzene (3ca)[18] (Table 2, Entry 3). Compound **3ca** was obtained from 1-(2,2-dibromovinyl)-2-methoxybenzene (**1c**) (72.1 mg) and *p*-tolylboronic acid (**2a**) (68.5 mg) according to the general procedure in 66% yield (36.2 mg,

0.163 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.51-7.45 (m, 3H), 7.33-7.27 (m, 1H), 7.15 (d, J = 7.9 Hz, 2H), 6.97-6.89 (m, 2H), 3.92 (s, 3H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.8, 133.5, 131.5, 138.2, 129.5, 129.0, 120.43, 120.38, 112.5, 110.6, 93.6, 84.9, 55.8, 21.5 ppm; EI-MS *m/z* (rel intensity) 222 (M^+, 100).

1-Methoxy-4-(*p*-tolylethynyl)benzene (3db)[18] (Table 2, Entry 4). Compound **3db** was obtained from 1-(2,2-dibromovinyl)-4-methylbenzene (**1d**) (6 .2 mg) and *p*-methoxyphenylboronic acid (**2b**) (75.7 mg) according to the general procedure in 54% yield (28.9 mg, 0.130 mmol) as a white solid; m.p. 125-126 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.46 (dt, J = 8.8, 2.8 Hz, 2H), 7.41 (d, J = 8.1 Hz, 2H), 7.14 (d, J = 8.1 Hz, 2H), 6.87 (dt, J = 8.8, 2.7 Hz, 2H), 3.83 (s, 3H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.4, 138.0, 132.9, 131.3, 129.1, 120.4, 115.5, 113.9, 88.6, 88.2, 55.3, 21.5 ppm; EI-MS *m/z* (rel intensity) 222 (M^+, 100).

1-((4-*tert*-Butylphenyl)ethynyl)-4-methoxybenzene (3eb)[21] (Table 2, Entry 5). Compound **3eb** was obtained from 1-(*tert*-butyl)-4-(2,2-dibromovinyl)benzene (**1e**) (79.3 mg) and *p*-methoxyphenylboronic acid (**2b**) (75.8 mg) according to the general procedure in 64% yield (42.1 mg, 0.159 mmol) as a white solid; m.p. 121-122 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.48-7.43 (m, 4H), 7.35 (dt, J = 8.5, 1.9 Hz, 2H), 6.86 (dt, J = 8.8, 2.7 Hz, 2H), 3.81 (s, 3H), 1.32 ppm (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.4, 151.1, 133.0, 131.1, 125.3, 120.5, 115.6, 113.9, 88.6, 88.1, 55.2, 34.7, 31.2 ppm; EI-MS *m/z* (rel intensity) 264 (M^+, 100).

1-((4-Chlorophenyl)ethynyl)-4-methoxybenzene (3fb)[12a] (Table 2, Entry 6). Compound **3fb** was obtained from 1-chloro-4-(2,2-dibromovinyl)benzene (**1f**) (73.9 mg) and *p*-methoxyphenylboronic acid (**2b**) (76.5 mg) according to the general procedure in 59% yield (35.8 mg, 0.148 mmol) as a white solid; m.p. 121-122 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.44 (tt, J = 8.8, 2.1 Hz, 4H), 7.30 (dt, J = 8.7, 2.0 Hz, 2H), 6.88 (dt, J = 8.9, 2.1 Hz, 2H), 3.83 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.8, 133.8, 133.1, 132.6, 128.6, 122.1, 115.0, 114.0, 90.3, 87.0, 55.3 ppm; EI-MS *m/z* (rel intensity) 242 (M^+, 100).

1-Methoxy-4-((4-(trifluoromethyl)phenyl)ethynyl)benzene (3gb)[11a] (Table 2, Entry 7). Compound **3gb** was obtained from 1-(2,2-dibromovinyl)-4-(trifluoromethyl)benzene (**1g**) (81.8 mg) and *p*-methoxyphenylboronic acid (**2b**) (76.1 mg) according to the general procedure in 65% yield (44.5 mg, 0.161 mmol) as a yellow solid; m.p. 112-114 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.59 (s, 4H), 7.49 (d, J = 8.6 Hz, 2H), 6.89 (d, J = 8.8 Hz, 2H), 3.84 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 160.0, 133.2, 131.6, 129.5 (q, J = 32.5 Hz), 127.4 (d, J = 1.1 Hz), 125.2 (q, J =3.9 Hz), 124.0 (d, J = 272.1 Hz), 114,6, 114.1, 91.9, 86.8, 55.3 ppm; EI-MS *m/z* (rel intensity) 276 (M^+, 100).

2-(*p*-Tolylethynyl)naphthalene (3ha)[18] (Table 2, Entry 8). Compound **3ha** was obtained from 2-(2,2-dibromovinyl)naphthalene (**1h**) (77.0 mg) and *p*-tolylboronic acid (**2a**) (68.5 mg) according to the general procedure in 81% yield (48.8 mg, 0.201 mmol) as a white solid; m.p. 137-139 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.04 (s, 1H), 7.83-7.79 (m, 3H), 7.57 (dd, J = 8.5, 1.6 Hz, 1H), 7.50-7.46 (m, 4H), 7.17 (d, J = 7.9 Hz, 2H), 2.38 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 138.4, 133.0, 132.7, 131.5, 131.2, 129.1, 128.4, 127.9, 127.7 (2C), 126.53, 126.47, 120.7, 120.1, 89.9, 89.1, 21.5 ppm; EI-MS *m/z* (rel intensity) 242 (M^+, 100).

1-(Methoxymethoxy)-2-(*p*-tolylethynyl)benzene (3ia) (Table 2, Entry 9). Compound **3ia** was obtained from 1-(2,2-dibromovinyl)-2-(methoxymethoxy)benzene (**1i**) (80.0 mg) and *p*-tolylboronic acid (**2a**) (68.4 mg) according to the general procedure in 73% yield (46.2 mg, 0.183 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.50 (dd, J = 7.7, 1.7 Hz, 1H), 7.44 (d, J = 8.1 Hz, 2H), 7.30-7.24 (m, 1H), 7.16-7.12 (m, 3H), 6.99 (td, J = 7.5, 1.1 Hz, 1H), 5.28 (s, 2H), 3.55 (s, 3H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 157.6, 138.2, 133.4, 131.4, 129.4, 129.0, 121.9, 120.4, 115.4, 114.1, 95.1, 93.4, 85.0, 56.3, 21.5 ppm; EI-MS *m/z* (rel intensity) 252 (M^+, 33); HRMS (ESI-orbitrap) calcd for $C_{17}H_{16}O_2$+Na [M+Na]$^+$: 275.1043, found: 275.1033.

1-Methoxy-4-(*m*-tolylethynyl)benzene (3ac)[18] (Table 2, Entry 10). Compound **3ac** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.0 mg) and *m*-tolylboronic acid (**2c**) (68.0 mg) according to the general procedure in 88% yield (48.5 mg, 0.218 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.46 (dt, J = 8.9, 2.8 Hz, 2H), 7.33 (d, J = 11.4 Hz, 2H), 7.22 (t, J = 8.1 Hz, 1H), 7.12 (d, J = 7.6 Hz, 1H), 6.87 (dt, J = 8.9, 2.8 Hz, 2H), 3.82 (s, 3H), 2.35 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.5, 137.9, 133.0, 132.0, 128.8, 128.5, 128.2, 123.3, 115.4, 113.9, 89.0, 88.2, 55.3, 21.2 ppm; EI-MS *m/z* (rel intensity) 222 (M^+, 100).

1-Methoxy-4-(*o*-tolylethynyl)benzene (3ad)[18] (Table 2, Entry 11). Compound **3ad** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.1 mg) and *o*-tolylboronic acid (**2d**) (68.4 mg) according to the general procedure in 64% yield (35.1 mg, 0.158 mmol) as a white solid; m.p. 77-78 °C ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.47 (d, J = 8.9 Hz, 3H), 7.23-7.16 (m, 3H), 6.88 (d, J = 8.9 Hz, 2H), 2.51 (s, 3H), 3.83 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.5, 139.9, 132.9, 131.6, 129.4, 127.9, 125.5, 123.3 115.6, 114.0, 93.3, 87.0, 55.3, 20.8 ppm; EI-MS *m/z* (rel intensity) 222 (M^+, 100).

1-Methoxy-4-(phenylethynyl)benzene (3ae)[18] (Table 2, Entry 12). Compound **3ae** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.7 mg) and phenylboronic acid (**2e**) (60.7 mg) according to the general procedure in 60% yield (31.1 mg, 0.150 mmol) as a yellow solid; m.p. 56-57 °C ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.53-7.45 (m, 4H), 7.36-7.31 (m, 3H), 6.90-6.86 (m, 2H), 3.83 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.6, 133.0, 131.4, 128.3, 127.9, 123.6, 115.3, 114.0, 89.3, 88.0, 55.3 ppm; EI-MS *m/z* (rel intensity) 208 (M^+, 100).

1-((4-Chlorophenyl)ethynyl)-4-methoxybenzene (3af)[18] (Table 2, Entry 13). Compound **3af** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.1 mg) and 4-chlorophenylboronic acid (**2f**) (78.6 mg) according to the general procedure in 65% yield (38.9 mg, 0.161 mmol) as a yellow solid; m.p.121-123 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.48-7.42 (m, 4H), 7.31 (d, J = 8.6 Hz, 2H), 6.88 (d, J = 8.8 Hz, 2H), 3.83 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.7, 133.8, 133.0, 132.6,

128.6, 122.1, 114.9, 114.0, 90.3, 87.0, 55.3 ppm; EI-MS *m/z* (rel intensity) 242 (M^+, 100).

1-((4-Bromophenyl)ethynyl)-4-methoxybenzene (3ag)[12a] (Table 2, Entry 14). Compound **3ag** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.5 mg) and 4-bromophenylboronic acid (**2g**) (100.9 mg) according to the general procedure in 54% yield (38.8 mg, 0.135 mmol) as a white solid; m.p.150-151 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.48-7.45 (m, 4H), 7.36 (d, *J* = 8.5 Hz, 2H), 6.88 (d, *J* = 8.9 Hz, 2H), 3.83 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.7, 133.0, 132.8, 131.5, 122.5, 122.0, 114.9, 114.0, 90.5, 87.0, 55.3 ppm; EI-MS *m/z* (rel intensity) 286 (M^+, 100).

1-Methoxy-4-((4-(trifluoromethyl)phenyl)ethynyl)benzene (3ah)[18] (Table 2, Entry 15). Compound **3ah** was obtained from 1-(2,2-dibromovinyl)-4-(trifluoromethyl)benzene (**1a**) (72.5 mg) and 4-(trifluoromethyl)phenylboronic acid (**2h**) (95.2 mg) according to the general procedure in 44% yield (30.3 mg, 0.110 mmol) as a white solid; m.p. 86-88 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.59 (s, 4H), 7.48 (dt, *J* = 8.9, 2.7 Hz, 2H), 6.89 (dt, *J* = 8.9, 2.7 Hz, 2H), 3.83 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 160.0, 133.2, 131.6, 129.5 (q, *J* = 32.6 Hz), 127.5 (q, *J* = 1.1 Hz), 125.2 (q, *J* = 3.7 Hz), 124.0 (q, *J* = 272.0 Hz), 114.6, 114.1, 91.9, 86.8, 55.3 ppm; EI-MS *m/z* (rel intensity) 276 (M^+, 100).

2-((4-Methoxyphenyl)ethynyl)thiophene (3ai)[10b] (Table 2, Entry 16). Compound **3ai** was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.7 mg) and 3-thiophenylboronic acid (**2i**) (64.4 mg) according to the general procedure in 27% yield (14.5 mg, 0.0678 mmol) as a yellow solid; m.p.53-55 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.49-7.44 (m, 3H), 7.30-7.28 (m, 1H), 7.18 (dd, *J* = 5.0, 1.1 Hz, 1H), 6.87 (d, *J* = 8.8 Hz, 2H), 3.82 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.5, 132.9, 129.8, 128.0, 125.2, 122.5, 115.2, 113.9, 88.7, 83.1, 55.3 ppm; EI-MS *m/z* (rel intensity) 214 (M^+, 100).

2-(4-Methoxyphenyl)benzofuran[19] (Table 2, Entry 17). 2-(4-Methoxyphenyl)benzofuran was obtained from 1-(2,2-dibromovinyl)-4-methoxybenzene (**1a**) (72.2 mg) and 2-hydroxyphenylboronic acid (**2j**) (69.4 mg) according to the general procedure in 10% yield (14.5 mg, 0.0254 mmol) as a white solid; m.p.150-151 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.80 (dt, *J* = 8.9, 2.8 Hz, 2H), 7.57-7.49 (m, 2H), 7.18-7.18 (m, 2H), 6.98 (dt, *J* = 8.8, 2.9 Hz, 2H), 6.89 (s, 1H), 3.86 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.9, 156.0, 154.6, 129.4, 126.4, 123.7, 123.3, 122.8, 120.5, 114.2, 111.0, 99.6, 55.4 ppm; EI-MS *m/z* (rel intensity) 224 (M^+, 100).

1-(Bromoethynyl)-2-(methoxymethoxy)benzene (1i')[22] (Table 2, Entry 18). Compound **1i'** was obtained from 1-(2,2-dibromovinyl)-4-(methoxymethoxy)benzene (**1i**) (79.6 mg) and 2-bromophenylboronic acid (**2k**) (100.8 mg) according to the general procedure in 63% yield (37.8 mg, 0.158 mmol) as a yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.42 (dd, *J* = 7.6, 1.7 Hz, 1H), 7.28 (dt, *J* = 8.5, 1.7 Hz, 1H), 7.11 (d, *J* = 7.5 Hz, 1H), 6.95 (td, *J* = 7.6, 1.1 Hz, 1H), 5.24 (s, 2H), 3.52 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.4, 133.9, 130.0, 121.7, 115.1, 113.1, 94.9, 76.4, 56.3, 52.9 ppm; EI-MS *m/z* (rel intensity) 240 (M^+, 10).

1-Allyloxy-2-(*p*-tolylethynyl)benzene (5a) (Table 3, Entry 1). Compound **5a** was obtained from 1-allyloxy-2-(2,2-dibromovinyl)benzene (**4a**) (79.1 mg) and *p*-tolylboronic acid (**2a**) (67.8 mg) according to the general procedure in 75% yield (46.9 mg, 0.189 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.49 (dd, *J* = 7.5, 1.7 Hz, 1H) 7.44 (d, *J* = 8.1 Hz, 2H), 7.29-7.23 (m, 1H), 7.15 (d, *J* = 7.9 Hz, 2H), 6.96-6.87 (m, 2H), 6.16-6.04 (m, 1H), 5.54 (dq, *J* = 17.3, 1.6 Hz, 1H), 5.30 (dq, *J* =10.6, 1.6 Hz, 1H), 4.64 (dt, *J* = 4.8, 1.6 Hz, 2H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.0, 138.1, 133.3, 133.0, 131.4, 129.4, 129.0, 120.7, 120.6, 117.1, 113.3, 112.5, 93.7, 85.1, 69.2, 21.5 ppm; EI-MS *m/z* (rel intensity) 248 (M^+, 100); HRMS (APCI-orbitrap) calcd for $C_{18}H_{16}O$+H $[M+H]^+$: 249.1274, found: 249.1263.

1-Allyloxy-4-chloro-2-(*p*-tolylethynyl)benzene (5b) (Table 3, Entry 2). Compound **5b** was obtained from 1-allyloxy-4-chloro-2-(2,2-dibromovinyl)benzene (**4b**) (88.0 mg) and *p*-tolylboronic acid (**2a**) (68.4 mg) according to the general procedure in 83% yield (59.2 mg, 0.210 mmol) as a yellow solid; m.p. 36-37 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.46-7.42 (m, 3H), 7.23-7.15 (m, 3H), 6.81 (d, *J* = 8.9 Hz, 1H), 6.14-6.01 (m, 1H), 5.53 (dd, *J* = 17.2, 1.6 Hz, 1H), 5.32 (dd, *J* = 10.6, 1.4 Hz, 1H), 4.61 (dt, *J* = 4.8, 1.5 Hz, 2H), 2.37 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.6, 138.6, 132.7, 132.6, 131.5, 129.09, 129.06, 125.4, 120.0, 117.4, 114.9, 113.6, 94.8, 83.8, 69.6, 21.5 ppm; EI-MS *m/z* (rel intensity) 282 (M^+, 100); HRMS (APCI-orbitrap) calcd for $C_{18}H_{15}OCl$+H $[M+H]^+$: 283.0884, found: 283.0879.

1-Allyloxy-4-methyl-2-(*p*-tolylethynyl)benzene (5c) (Table 3, Entry 3). Compound **5c** was obtained from 1-allyloxy-2-(2,2-dibromovinyl)-4-methylbenzene (**4c**) (82.5 mg) and *p*-tolylboronic acid (**2a**) (67.8 mg) according to the general procedure in 74% yield (48.8 mg, 0.186 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.43 (d, *J* = 8.0 Hz, 2H), 7.31 (d, *J* = 1.7 Hz, 1H), 7.14 (d, *J* = 7.9 Hz, 2H), 7.05 (dd, *J* = 8.4, 16.0 Hz, 1H), 6.63 (d, *J* = 8.4 Hz, 1H), 6.15-6.03 (m, 1H), 5.52 (dd, *J* = 17.2, 1.6 Hz, 1H), 5.29 (dd, *J* = 10.6, 1.5 Hz, 1H), 4.61-4.59 (m, 2H), 2.35 (s, 3H), 2.27 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 156.9, 138.0, 133.7, 133.2, 131.4, 130.0, 129.9, 129.0, 120.6, 117.0, 113.0, 112.6, 93.4, 85.2, 69.4, 21.5, 20.3 ppm; EI-MS *m/z* (rel intensity) 262 (M^+, 100); HRMS (APCI-orbitrap) calcd for $C_{19}H_{18}O$+H $[M+H]^+$: 263.1430, found: 263.1424.

1-Allyloxy-4-methoxy-2-(*p*-tolylethynyl)benzene (5d) (Table 3, Entry 4). Compound **5d** was obtained from 1-allyloxy-2-(2,2-dibromovinyl)-4-methoxybenzene (**4d**) (86.0 mg) and *p*-tolylboronic acid (**2a**) (68.5 mg) according to the general procedure in 78% yield (54.2 mg, 0.195 mmol) as a white solid; m.p. 74-75 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.44 (d, *J* = 8.1 Hz, 2H), 7.15 (d, *J* = 7.9 Hz, 2H), 7.03 (dd, *J* = 2.4, 1.0 Hz, 1H), 6.86-6.79 (m, 2H), 6.15-6.03 (m, 1H), 5.51 (dq, *J* = 17.3, 1.7 Hz, 1H), 5.28 (dq, *J* = 10.6, 1.5 Hz, 1H), 4.59 (dt, *J* = 4.9, 1.6 Hz, 2H), 3.78 (s, 3H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 153.53, 153.46, 138.3, 133.4, 131.5, 129.0, 120.4, 117.6, 117.1, 115.5, 114.7, 114.2, 93.7, 85.0, 70.4, 55.7, 21.5 ppm; EI-MS *m/z* (rel intensity) 278 (M^+, 100); HRMS (APCI-orbitrap) calcd for $C_{19}H_{18}O_2$+H $[M+H]^+$: 279.1380, found: 279.1370.

1-Cinnamyloxy-2-(*p*-tolylethynyl)benzene (5e) (Table 3, Entry 5). Compound **5e** was obtained from 1-cinnamyloxy-2-(2,2-

dibromovinyl)benzene (**4e**) (98.4 mg) and *p*-tolylboronic acid (**2a**) (68.4 mg) according to the general procedure in 80% yield (64.8 mg, 0.200 mmol) as a white solid; m.p. 76-78 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.51 (dd, *J* = 7.9, 1.5 Hz, 1H), 7.46 (d, *J* = 8.1 Hz, 2H), 7.41-7.22 (m, 6H), 7.14 (d, *J* = 7.9 Hz, 2H), 6.97-6.93 (m, 2H), 6.86 (d, *J* = 16.0 Hz, 1H), 6.46 (dt, *J* = 16.0, 5.2 Hz, 1H), 4.81 (dd, *J* = 5.3 1.5 Hz, 2H), 2.36 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.0, 138.2, 136.6, 133.4, 132.3, 131.5, 129.4, 129.0, 128.5, 127.7, 126.5, 124.4, 120.8, 120.5, 113.4, 112.7, 93.8, 85.1, 69.2, 21.5 ppm; EI-MS *m/z* (rel intensity) 324 (M^+, 18); HRMS (APCI-orbitrap) calcd for $C_{24}H_{20}O$+H $[M+H]^+$: 325.1587, found: 325.1574.

1-((3-Methylbut-2-en-1-yl)oxy)-2-(*p*-tolylethynyl)benzene (5f) (Table 3, Entry 6). Compound **5f** was obtained from 1-(2,2-dibromovinyl)-2-((3-Methylbut-2-en-1-yl)oxy)benzene (**4f**) (86.3 mg) and *p*-tolylboronic acid (**2a**) (67.7 mg) according to the general procedure in 86% yield (59.4 mg, 0.215 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.49-7.42 (m, 3H), 7.29-7.23 (m, 1H), 7.14 (d, *J* = 8.1 Hz, 2H), 6.95-6.88 (m, 2H), 5.56-5.52 (m, 1H), 4.64 (d, *J* = 6.4 Hz, 2H), 2.36 (s, 3H), 1.79 (s, 3H), 1.75 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.3, 138.0, 137.3, 133.4, 131.5, 129.3, 129.0, 120.7, 120.5, 120.0, 113.4, 112.7, 93.5, 85.3, 65.9, 25.8, 21.5, 18.3 ppm; EI-MS *m/z* (rel intensity) 276 (M^+, 8); HRMS (ESI-orbitrap) calcd for $C_{20}H_{20}O$+H $[M+H]^+$: 277.1587, found: 277.1587.

1-Allyloxy-2-(phenylethynyl)benzene (5g)[18] (Table 3, Entry 7). Compound **5g** was obtained from 1-allyloxy-2-(2,2-dibromovinyl)benzene (**4a**) (79.1 mg) and phenylboronic acid (**2e**) (61.4 mg) according to the general procedure in 75% yield (45.4 mg, 0.194 mmol) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.56-7.49 (m, 3H), 7.38-7.28 (m, 4H), 6.97-6.88 (m, 2H), 6.15-6.04 (m, 1H), 5.55 (dq, *J* = 17.3, 1.7 Hz, 1H), 5.31 (dq, *J* = 10.6, 1.6 Hz, 1H), 4.64 ppm (dt, *J* = 4.8, 1.5 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.0, 133.4, 133.0, 131.5, 129.6, 128.2, 128.0, 123.6, 120.7, 117.1, 113.0, 112.4, 93.5, 85.7, 69.2 ppm; EI-MS *m/z* (rel intensity) 234 (M^+, 62).

Heck-type reaction of *o*-allyloxyethynylbenzene (Scheme 1)

A mixture of 1-allyloxy-2-(phenylethynyl)benzene **5g** (70.7 mg, 0.30 mmol), *p*-iodetoluene (21.8 mg, 0.10 mmol), K_3PO_4 (63.6 mg, 0.30 mmol), $Pd(OAc)_2$ (10.0 µmol, 2.97 mg) and ligand **L1c** (10.0 µmol, 1.92 mg) in DMF (0.4 mL) at 70 °C under an Ar atmosphere was stirred for 18 h. After the reaction, the reaction was quenched with distilled water. The solution was extracted with ethyl acetate, washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was purified by silica gel chromatography (hexane/toluene (v/v = 10/1) afford (*E*)-1-(phenylethynyl)2-((3-(*p*-tolyl)allyl)oxy)benzene (**6**) in 23% yield (7.5 mg, 0.0233 mmol).

(*E*)-1-(Phenylethynyl)-2-((3-(*p*-tolyl)allyl)oxy)benzene (6).[20h] Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ =7.58-7.50 (m, 3H), 7.35-7.26 (m, 6H), 7.13 (d, *J* = 8.0 Hz, 2H), 6.98-6.93 (m, 2H), 6.82 (d, *J* = 16.1 Hz, 1H), 6.41 (dt, *J* = 15.9, 5.4 Hz, 1H), 4.80 (dd, *J* = 5.3, 1.4 Hz, 2H), 2.34 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.1, 137.6, 133.7, 133.4, 132.3, 131.6, 129.6, 129.3, 128.3, 128.1, 126.4, 123.6, 123.2, 120.8, 112.6, 113.1, 93.6, 85.8, 69.3, 21.2 ppm; EI-MS *m/z* (rel intensity) 324 (M^+, 4).

Acknowledgements

This work was supported by a Grant-in-Aid for Scientific Research (C) (No. 26410109) from Japan Society for the Promotion of Science (JSPS). We thank the Tonen General Sekiyu Research and Development Encouragement Foundation and a Leading Research Promotion Program "Soft Molecular Activation" of Chiba University for financial support.

Keywords: copper • coupling reaction • alkyne • dibromoalkene

[1] a) L. X. Yin, J. Liebscher, *Chem. Rev.* **2007**, *107*, 133-173; b) A. B. Flynn, W. W. Ogilvie, *Chem. Rev.* **2007**, *107*, 4698-4745; c) M. C. Pacheco, S. Purser, V. Gouverneur, *Chem. Rev.* **2008**, *108*, 1943-1981; d) G. Evano, N. Blanchard, M. Toumi, *Chem. Rev.* **2008,** *108*, 3054-3131; e) B. B. Touré, D. G. Hall, *Chem. Rev*. **2009**, *109*, 4439-4486; f) J. Magano, J. R. Dunetz, *Chem. Rev*. **2011**, *111*, 2177-2250.

[2] a) R. J. Madhushaw, C.-Y. Lo, C.-W. Hwang, M.-D. Su, H.-C. Shen, S. Pal, I. R. Shaikh, R.-S. Liu, *J. Am. Chem. Soc.* **2004**, *126*, 15560–15565; b) R. Yanada, S. Obika, T. Inokuma, K. Yanada, M. Yamashita, S. Ohta, Y. Takemoto, *J. Org. Chem.* **2005**, *70*, 6972–6975; c) I. Nakamura, Y. Mizushima, Y. Yamamoto, *J. Am. Chem. Soc.* **2005**, *127*, 15022–15023; d) M. Nakamura, L. Ilies, S. Otsubo, E. Nakamura, *Org. Lett.* **2006**, *8*, 2803-2805; e) T. Shibata, Y. Ueno, K. Kanda, *Synlett* **2006**, 411–414; f) K. Tanaka, K. Sasaki, K. Takeishi, M. Hirano, *Eur. J. Org. Chem.* **2007**, 5675–5685; g) M. M. Heravi, S. Sadjadi, *Tetrahedron* **2009**, *65*, 7761–7775; h) C. Kanazawa, K. Goto, M. Terada, *Chem. Commun.* **2009**, 5248–5250; i) J. Renault, Z. Qian, P. Uriac, N. Gouault, *Tetrahedron Lett.* **2011**, *52*, 2476–2479; j) M. Jiang, T. Jiang, J.-E. Bäckvall, *Org. Lett.* **2012**, *14*, 3538–3541; k) J. Fu, H. Shang, Z. Wang, L. Chang, W. Shao, Z. Yang, Y. Tang, *Angew. Chem. Int. Ed.* **2013**, *52*, 4198–4202; l) S. K. Alamsetti, A. K. Å. Persson, J.-E. Bäckvall, *Org. Lett.* **2014**, *16*, 1434–1437; m) T. Lauterbach, T. Higuchi, M. W. Hussong, M. Rudolph, F. Rominger, K. Mashima, A. S. K. Hashmi, *Adv. Synth. Catal.* **2015**, *357*, 775–781; n) J. Li, Z. Zhu, S. Yang, Z. Zhang, W. Wu, H. Jiang, *J. Org. Chem.* **2015**, *80*, 3870-3879; o) T. Otani, K. Ueki, K. Cho, K. Kanai, K. Tateno, T. Saito, *Chem. Commun.* **2015**, *51*, 7895–7898; p) J. Das, S. S. Bag, A. Basak, *J. Org. Chem.* **2016**, *81*, 4623–4632; q) J. Wang, J. Yao, H. Wang, H. Chen, J. Dong, H. Zhou, *J. Org. Chem.* **2016**, *81*, 5250–5255; r) S. Matsumoto, S. Kikuchi, N. Norita, H. Masu, M. Akazome, *J. Org. Chem.* **2016**, *81*, 5322–5329; s) T. Harris, G. D. P. Gomes, R. J. Clark, I. V. Alabugin, *J. Org. Chem.* **2016**, *81*, 6007–6017; t) T. Vacala, L. P. Bejcek, C. G. Williams, A. C. Williamson, P. A. Vadola, *J. Org. Chem.* **2017**, *82*, 2558-2569; u) J. Bucher, T. Wurm, S. Taschinski, E. Sachs, D. Ascough, M. Rudolph, F. Rominger, A. S. K. Hashmi, *Adv. Synth. Catal.* **2017**, *359*, 225–233.

[3] a) K. Sonogashira, Y. Tohda, N. Hagihara, *Tetrahedron Lett.* **1975**, *16*, 4467–4470; b) K. Sonogashira, *J. Organomet. Chem.* **2002**, *653*, 46–49; c) E. Negishi, L. Anastasia, *Chem. Rev.* **2003**, *103*, 1979–2017; d) R. Chinchilla, C. Nájera, *Chem. Rev.* **2007**, *107*, 874–922; e) R. Chinchilla, C. Nájera, *Chem. Soc. Rev.* **2011**, *40*, 5084–5121.

[4] a) R. K. Gujadhur, C. G. Bates, D. Venkataraman, *Org. Lett.* **2001**, *3*, 4315–4317; b) D. Ma, F. Liu, *Chem. Commun.* **2004**, *3*, 1934–1935; c) M. B. Thathagar, J. Beckers, G. Rothenberg, *Green Chem.* **2004**, *6*, 215–218; d) J.-H. Li, J.-L. Li, D.-P. Wang, S.-F. Pi, Y.-X. Xie, M.-B. Zhang, X.-C. Hu, *J. Org. Chem.* **2007**, *72*, 2053–2057; e) B.-X. Tang, F. Wang, J.-H. Li, Y.-X. Xie, M.-B. Zhang, *J. Org. Chem.* **2007**, *72*, 6294–6297; f) A.

Biffis, E. Scattolin, N. Ravasio, F. Zaccheria, *Tetrahedron Lett.* **2007**, *48*, 8761–8764; g) F. Monnier, F. Turtaut, L. Duroure, M. Taillefer, *Org. Lett.* **2008**, *10*, 3203–3206; h) M. Wu, J. Mao, J. Guo, S. Ji, *Eur. J. Org. Chem.* **2008**, 4050–4054; i) K. G. Thakur, E. A. Jaseer, A. B. Naidu, G. Sekar, *Tetrahedron Lett.* **2009**, *50*, 2865–2869; j) E. Zuidema, C. Bolm, *Chem. Eur. J.* **2010**, *16*, 4181–4185; k) A. Sagadevan, K. C. Hwang, *Adv. Synth. Catal.* **2012**, *354*, 3421–3427; l) S. Dhara, R. Singha, M. Ghosh, A. Ahmed, Y. Nuree, A. Das, J. K. Ray, *RSC Adv.* **2014**, *4*, 42604–42607; m) C.-X. Lin, J.-F. Zhu, Q.-S. Li, L.-H. Ao, Y.-J. Jin, F.-B. Xu, F.-Z. Hu, Y.-F. Yuan, *Appl. Organometal. Chem.* **2014**, *28*, 298–303; n) P. Rani, R. Srivastava, *Tetrahedron Lett.* **2014**, *55*, 5256–5260; o) A. M. Thomas, A. Sujatha, G. Anilkumar, *RSC Advances* **2014**, *4*, 21688-21689; p) W. Xu, B. Yu, H. Sun, G. Zhang, W. Zhang, Z. Gao, *Appl. Organometal. Chem.* **2015**, *29*, 353–356.

[5] L. Wang, P. Li, Y. Zhang, *Chem. Commun.* **2004**, 514–515.

[6] M. Carril, A. Correa, C. Bolm, *Angew. Chem. Int. Ed.* **2008**, *47*, 4862–4865.

[7] a) Y. Shi, X. Li, J. Liu, W. Jiang, L. Sun, *Appl. Organometal. Chem.* **2011**, *25*, 514–520; b) X. Zhang, P. Li, Y. Ji, L. Zhang, L. Wang, *Synthesis* **2011**, 2975–2983; c) J.-S. Tang, M. Tian, W.-B. Sheng, C.-C. Guo, *Synthesis* **2012**, 541–546.

[8] S. Wang, M. Wang, L. Wang, B. Wang, P. Li, J. Yang, *Tetrahedron* **2011**, *67*, 4800–4806.

[9] a) G. Chelucci, F. Capitta, G. A. Pinna, *Tetrahedron Lett.* **2007**, *48*, 6514–6517; b) G. Chelucci, F. Capitta, S. Baldino, *Tetrahedron* **2008**, *64*, 10250–10257.

[10] a) W. Shen, L. Wang, *J. Org. Chem.* **1999**, *64*, 8873–8879; b) M. L. N. Rao, D. N. Jadhav, P. Dasgupta, *Org. Lett.* **2010**, *12*, 2048–2051; c) A. Rahimi, A. Schmidt, *Synthesis* **2010**, 2621–2625.

[11] a) E. J. Corey, P. L. Fuchs, *Tetrahedron Lett.* **1972**, 3769–3772; b) F. Eymery, B. Iorga, P. Savignac, *Synthesis* 185-213; c) G. Chelucci, *Chem. Rev.* **2012**, *112*, 1344–1462.

[12] a) J. Liu, F. Dai, Z. Yang, S. Wang, K. Xie, A. Wang, X. Chen, Z. Tan, *Tetrahedron Lett.* **2012**, *53*, 5678–5683; b) H. Yan, L. Lu, P. Sun, Y. Zhu, H. Yang, D. Liu, G. Rong, J. Mao, *RSC Adv.* **2013**, *3*, 377–381.

[13] a) T. Mino, Y. Shirae, M. Sakamoto, T. Fujita, *Synlett* **2003**, 882-884; b) T. Mino, Y. Shirae, M. Sakamoto, T. Fujita, *J. Org. Chem.* **2005**, *70*, 2191–2194.

[14] a) T. Mino, Y. Shirae, Y. Sasai, M. Sakamoto, T. Fujita, *J. Org. Chem.* **2006**, *71*, 6834–6839; b) T. Mino, H. Shindo, T. Kaneda, T. Koizumi, Y. Kasashima, M. Sakamoto, T. Fujita, *Tetrahedron Lett.* **2009**, *50*, 5358–5360; c) T. Mino, M. Shibuya, S. Suzuki, K. Hirai, M. Sakamoto, T. Fujita, *Tetrahedron* **2012**, *68*, 429–432; d) T. Mino, M. Shibuya, S. Suzuki, K. Hirai, M. Sakamoto, T. Fujita, *Tetrahedron* **2012**, *68*, 429-432.

[15] a) T. Mino, Y. Shirae, T. Saito, M. Sakamoto, T. Fujita, *J. Org. Chem.* **2006**, *71*, 9499–9502; b) T. Mino, S. Suzuki, K. Hirai, M. Sakamoto, T. Fujita, *Synlett* **2011**, 1277-1280.

[16] T. Mino, F. Yagishita, M. Shibuya, K. Kajiwara, H, Shindo, M. Sakamoto, T. Fujita, *Synlett* **2009**, 2457-2460.

[17] T. Mino, Y. Harada, H. Shindo, M. Sakamoto, T. Fujita, *Synlett* **2008**, 614-620.

[18] K. Watanabe, T. Mino, E. Ishikawa, M. Okano, T. Ikematsu, Y. Yoshida, M. Sakamoto, K. Sato, K. Yoshida, *Eur. J. Org. Chem.* **2017**, 2359-2368.

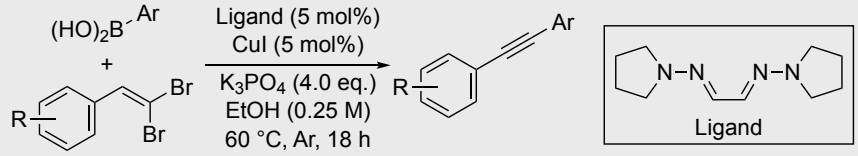
[19] D. Y. Li, K. J. Shi, X. F. Mao, Z. L. Zhao, X. Y. Wu, P. N. Liu, *Tetrahedron* **2014**, 70, 7022–7031.

[20] a) S. Cacchi, G. Fabrizi, L. Moro, *Synlett* **1998**, 741–745; b) N. Monteiro, G. Balme, *Synlett* **1998**, 746–747; c) C. J. Lovely, H. Seshadri, *Synth. Commun.* **2001**, *31*, 2479–2490; d) A. Fürstner, P. W. Davies, *J. Am. Chem. Soc.* **2005**, *127*, 15024–15025; e) Z. Liang, S. Ma, J. Yu, R. Xu, *J. Org. Chem.* **2007**, *72*, 9219–922; f) R. Okamoto, E. Okazaki, K. Noguchi, K. Tanaka, *Org. Lett.* **2011**, *13*, 4894-4897; g) C. Kanazawa, K. Goto, M. Terada, *Chem. Commun.* **2009**, 5248–5250; h) K. Watanabe, T. Mino, T. Ikematsu, C. Hatta, Y. Yoshida, M. Sakamoto, *Org. Chem. Front.* **2016**, *3*, 979–984.

[21] Y. Yang, X. Chew, C. W. Johannes, E. G. Robins, H. Jong, Y. H. Lim, *Eur. J. Org. Chem.* **2014**, 7184–7192.

[22] M. C. B. Jaimes, V. Weingand, F. Rominger, A. S. K. Hashmi, *Chem. Eur. J.* **2013**, *19*, 12504–12511.

FULL PAPER



We found that hydrazone-Cu-catalyzed Suzuki-Miyaura-type reaction of (2,2-dibromovinyl)benzene derivatives with arylboronic acids proceeded smoothly at 60 °C using 5 mol% of Cu-catalyst and afforded the corresponding internal alkyne products in good yields.

Cross-Coupling

Kohei Watanabe, Takashi Mino, Chikako Hatta, Eri Ishikawa, Yasushi Yoshida, and Masami Sakamoto*

Page No. – Page No.

Hydrazone-Cu-catalyzed Suzuki-Miyaura-type Reaction of Dibromoalkene with Arylboronic Acid