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Synthesis of Aryl- and Vinylacetylene Derivatives by Copper-Catalyzed Reaction of Aryl and Vinyl Iodides with Terminal Alkynes

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The coupling reaction of aryl iodides with terminal alkynes by using a catalyst system of CuI–PPh_3 in the presence of K_2CO_3 as base gives the corresponding arylated alkynes in excellent yields. Addition of PPh_3 is essential for the reaction to proceed catalytically. Vinyl iodides also react smoothly with the alkynes to give enyne compounds with retention of the configurations. While DMF and DMSO can be used as solvents, DMSO is found to be effective for the reaction with aliphatic terminal alkynes. A reaction mechanism involving initial formation of copper acetylide species coordinated by PPh_3 followed by reaction of aryl and vinyl iodides is proposed.

Introduction

Acetylene derivatives are versatile compounds in synthetic organic chemistry, and hence, various methods for their synthesis have been explored.[1] A conventional method for the preparation of arylacetylene derivatives is the coupling reaction of aryl halides with copper(I) acetylides, known as the Castro reaction.[2] Palladium-catalyzed coupling of aryl and vinyl halides with terminal alkynes[3] and with alkynylmetals[4] has also been developed and is now widely used for the synthesis of biologically active enyne compounds.[5] The reaction with terminal alkynes is often carried out using copper(I) iodide as a cocatalyst.[3c] On the other hand, Suzuki *et al.* have demonstrated that copper(I) species can promote the reaction of vinyl halides with terminal alkynes without employing palladium catalysts;[6] however, as in the Castro reaction a stoichiometric amount of copper salt is needed. By contrast, we found that aryl and vinyl iodides smoothly react with terminal alkynes in the presence of a catalytic amount of copper(I) iodide using potassium carbonate as base when an appropriate amount of triphenylphosphine is added,[7] giving the corresponding coupling products in good yields. While there have been numerous studies on copper-assisted substitution reactions of aryl halides,[8] reactions using a catalytic amount of copper salt are less common.[9] Consequently, we have carried out a detailed study of the scope and limitations of alkyne coupling reactions, including the stereochemistry of the reaction using vinyl halides as the substrates. The reaction under carbon monoxide has also been undertaken.

Results and Discussion

Reaction of Iodobenzene (1a) with Phenylacetylene (2a): Effect of Ligands and Copper Salts. The reaction of **1a** (2.0 mmol) with **2a** (2.0 mmol) was carried out using CuI (0.1 mmol) and K_2CO_3 (3.0 mmol) in DMF at 120 °C for 5 h in the presence of a number of phosphine ligands (eq 1 and Table I). While the reaction proceeded in the absence of the ligands, the yield of the coupling product, diphenylacetylene (**3a**), was very low. When PPh_3 was added to the reaction, the yield of **3a** was considerably increased, giving a maximum yield of a PPh_3/CuI ratio of 2.0. Other phosphorus-containing ligands tested, PPh_2Bu^n, PBu_3^n, and $P(OPh)_3$, were less effective. These results suggest that PPh_3 plays a crucial role in this reaction. An organic amine base, NBu_3^n, in place of K_2CO_3 suppressed the reaction.

$$\underset{\mathbf{1}}{\mathrm{ArX}} + \underset{\mathbf{2}}{\mathrm{HC{\equiv}CR}} \qquad (1)$$

1a: Ar = C_6H_5, X = I
b: Ar = 4-$NO_2C_6H_4$, X = I
c: Ar = 4-ClC_6H_4, X = I
d: Ar = 4-$CH_3C_6H_4$, X = I
e: Ar = 2-$CH_3OC_6H_4$, X = I
f: Ar = 1-naphthyl, X = I
g: Ar = 2-naphthyl, X = I
h: Ar = C_6H_5, X = Br
i: Ar = 4-$NO_2C_6H_4$, X = Br
j Ar = 2-$NO_2C_6H_4$, X = Br

2a: R = C_6H_5
b: R = n-C_5H_{11}
c: R = CH_2OH
d: R = CH_2OTHP
e: R = $CH_2OC(CH_3)_3$
f: R = CH_2OAc
g: R = $C(CH_3)_2OTHP$

$$\xrightarrow[\substack{K_2CO_3 \\ \text{DMF or DMSO}}]{\text{CuI}/\text{PPh}_3} \underset{\mathbf{3\text{–}13}}{\mathrm{ArC{\equiv}CR}}$$

3a: Ar = C_6H_5, R = C_6H_5
b: Ar = C_6H_5, R = n–C_5H_{11}
c: Ar = C_6H_5, R = CH_2OH
d: Ar = C_6H_5, R = CH_2OTHP
e: Ar = C_6H_5, R = $CH_2OC(CH_3)_3$
f: Ar = C_6H_5, R = $C(CH_3)_2OTHP$

5: Ar = 4-$NO_2C_6H_4$, R = C_6H_5
6: Ar = 4-ClC_6H_4, R = C_6H_5
7: Ar = 4-ClC_6H_4, R = n-C_5H_{11}
8: Ar = 4-$CH_3C_6H_4$, R = C_6H_5
9: Ar = 4-$CH_3C_6H_4$, R = n-C_5H_{11}
10: Ar = 2-$CH_3OC_6H_4$, R = C_6H_5
11: Ar = 1-naphthyl, R = C_6H_5
12: Ar = 2-naphthyl, R = C_6H_5
13: Ar = 2-$NO_2C_6H_4$, R = C_6H_5

Table II shows the results for the coupling reaction using various copper salts in the presence of PPh_3 (PPh_3/Cu =

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Table I. Effect of Ligands on Reaction of 1a with 2a[a]

L	L/CuI	yield of **3a**[b] (%)	recov of **1a**[b] (%)
		6	91
PPh_3	1.0	40	54
PPh_3	2.0	50	44
PPh_3	3.0	25	70
PPh_3	4.0	21	77
PPh_3[c]	2.0	7	72
PPh_2Bu^n	2.0	12	80
PBu_3^n	2.0	tr	95
$P(OPh)_3$	2.0	6	91

[a] Reaction conditions: **1a** (2.0 mmol), **2a** (2.0 mmol), CuI (0.1 mmol), K_2CO_3 (3.0 mmol), DMF (8 mL), 120 °C, 5 h. [b] Determined by GLC. [c] NBu_3^n (4.0 mmol) in place of K_2CO_3 was used as base.

Table II. Influence of Catalysts on Reaction of 1a with 2a[a]

cat.	time (h)	yield of **3a**[b] (%)	recov of **1a**[b] (%)
CuI	16	98[c]	0
CuI[d]	12	99	0
CuBr	16	95	3
CuCl	20	98	1
Cu_2O	20	7	91
$CuCl_2$	20	7	90
$Cu(OAc)_2$	20	88	5

[a] Reaction conditions: see footnote a in Table I. [b] Determined by GLC. [c] Isolated yield. [d] Reaction in DMSO.

Table III. Reaction of 1a with Several Terminal Alkynes 2b-g[a]

2	time (h)	yield of 3[b] (%)	recov of **1a**[b] (%)
2b[c]	45	**3b** (48)	(51)
2b[c,d]	45	**3b** (90)	(8)
2b	26	**3b**, 96	(2)
2c	36	**3c**	(80)
2d[e]	24	**3d**, 87	0
2e[e]	24	**3e**, 90	(10)
2f	26	**3f**, 37	(14)
2g[e]	48	**3g**, 44	(26)

[a] The reaction of **1a** (1.0–5.0 mmol) with **2a** (1.0–5.0 mmol) was carried out in DMSO (3–10 mL) at 120 °C under N_2 unless otherwise noted; [**1a**]:[**2**]:[CuI]:[PPh_3]:[K_2CO_3] = 1:1:0.05:0.1:1.5. [b] Isolated yield. Value in parentheses is GLC yield. [c] Reaction in DMF. [d] dppb (1,4-bis(diphenylphosphino)butane) in place of PPh_3 was used. [e] [CuI] = 0.1.

Table IV. Reaction of Aryl Halides 1b-j with Alkynes 2a or 2b[a]

1	2	time (h)	product, % yield
1b[b]	**2a**	16	**5**, 95
1c[b]	**2a**	24	**6**, 92
1c	**2b**	18	**7**, 96
1d[b]	**2a**	24	**8**, 95
1d	**2b**	46	**9**, 21[c]
1d[d]	**2b**	24	**9**, 75[e]
1e	**2a**	18	**10**, 84
1f	**2a**	24	**11**, 84
1g	**2a**	17	**12**, 92
1h	**2a**	48	**3a**, 8
1i	**2a**	22	**5**, 5
1j[b,f]	**2a**	24	**13**, 23[g]

[a] The reaction of **1a** (1.0–5.0 mmol) with **2a** was carried out in DMF (with **2a**) or DMSO (with **2b**) at 120 °C under N_2 unless otherwise noted; [**1**]:[**2**]:[CuI]:[PPh_3]:[K_2CO_3] = 1:1:0.1:0.1:1.5. [b] [CuI] = 0.05. [c] **1d** (75%) was recovered. [d] $CoCl_2$ was added. [$CoCl_2$] = 0.05. [e] **1d** (21%) was recovered. [f] Reaction in DMSO. [g] Nitrobenzene (21%) and **4** (16%) were formed as byproducts.

2.0). With CuI, the starting materials **1a** and **2a** were completely consumed in a period of 16 h, and the product **3a** was obtained quantitatively. The reaction in DMSO, in place of DMF, was found to be completed within 12 h. While both CuBr and CuCl could be successfully used, Cu_2O was ineffective. A divalent copper salt, $Cu(OAc)_2$, also showed good catalytic activity, giving **3a** in 88% yield along with 1,4-diphenylbutadiyne (**4**) (5%). It is known that $Cu(OAc)_2$ can oxidize terminal alkynes to give diynes,[10] and therefore, in the present reaction, $Cu(OAc)_2$ appears to be transformed to a catalytically active copper(I) species, accompanied by formation of **4**. In contrast, the reaction using $CuCl_2$ was unsuccessful.

Reaction with Various Aryl Halides 1 and Terminal Alkynes 2. Table III summarizes the results for the reaction of **1a** with alkynes **2b-g**. The reaction with 1-heptyne (**2b**) was successfully carried out in DMSO, the product 1-phenyl-1-heptyne (**3b**) being produced in a yield of 96% within 26 h. While the reaction in DMF was rather slow, the use of 1,4-bis(diphenylphosphino)butane (dppb) in place of PPh_3 was found to accelerate the reaction, interestingly. The reaction with propargyl alcohol (**2c**) did not afford the expected product **3c**. This is in contrast to the fact that allylic chlorides smoothly react with **2c** in the presence of a catalytic amount of copper(I) species.[11] However, protection of **2c** with tetrahydropyranyl (THP), *tert*-butyl, and acetyl groups enabled the reaction to give the corresponding coupled products in 37–90% yields. These compounds may also be transformed into **3c** on treatment with an acid.[12] On the other hand, the reaction with methyl propiolate was unsuccessful.

Table IV shows the results for the reaction of various aryl halides with **2a** or **2b**. The reaction of 4-substituted iodobenzenes **1b-d** with **2a** gave the corresponding diphenylacetylene derivatives **5**, **6**, and **8** in excellent yields. Similarly, 1-iodo-2-methoxybenzene (**1e**) and 1- (**1f**) and 2-iodonaphthalenes (**1g**) also reacted smoothly to afford products **10-12**. The reactions with bromobenzene (**1h**) and 1-bromo-4-nitrobenzene (**1i**) with **2a** did not, however, proceed catalytically, whereas 1-bromo-2-nitrobenzene (**1j**) did to some extent.[13] The reaction of **1c** and **2b** in DMSO proceeded smoothly, as in the analogous reaction using **1a**. In contrast, **1d** reacted with **2b** very slowly; however, it was of interest that addition of cobalt(II) chloride (0.05 equiv) remarkably enhanced this reaction.

The Castro reaction using aryl halides having an *ortho*-nucleophilic substituent such as -COOH, -OH, or $-NH_2$ is a useful method for preparation of certain heterocyclic compounds.[2] Consequently, reaction of 2-substituted iodobenzenes **1k-o** with **2a** was examined under the present reaction conditions (Table V). The reaction of 2-iodobenzoic acid (**1k**) gave 3-phenylisocoumarin (**14**) (19%) along with several unidentified products. This contrasts the Castro reaction, which produces 3-benzylidenephthalide exclusively.[2c] When methyl 2-iodobenzoate (**1l**) was reacted, **14** (53%) was also produced together with the normal coupling product **15** (42%). However, addition of H_2O (1 equiv) to the reaction resulted in the selective

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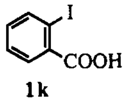
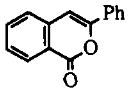
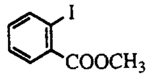
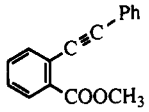
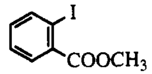
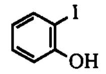
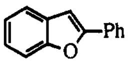
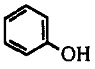
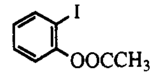
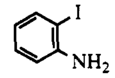
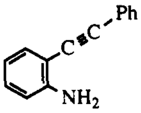
(13) It has been reported that in copper-assisted nucleophilic substitution reactions of aryl halides the presence of a nitro group at the *ortho*-position considerably enhances the reaction.[9]

Table V. Reaction of 2-Substituted 1-Iodobenzenes (1k-o) with Phenylacetylene (2a)[a]

1	product(s), % yield		
 **1k**	 14, 19		
 **1l**	14, 53	 15, 42	
 **1l**[b]	14, 3	15, 70	
 **1m**	 16, 18	 17, 15	4, 15
 **1n**[c]	16, 54	17, 25	4, 20
 **1o**[d]	 18, 78	4, 8	

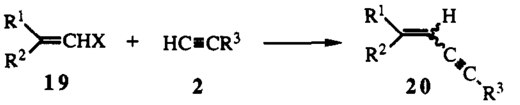
[a] Reaction conditions: see footnote a in Table IV. Reaction for 24 h. [b] H_2O (1.0 equiv to **1l**) was added. [c] Reaction for 20 h. [d] Reaction for 41 h. **1o** (14%) was recovered.

Table VI. Reaction of Vinyl Halides 19a-f with Alkynes 2a-e[a]

vinyl halide **19** (*E*/*Z*)	alkyne **2**	time (h)	yield (%) **20**	*E*/*Z*
PhCH=CHBr (**19a**, >99/1)	**2a**	24	**20a**, 88	>99/1
	2b[b]	24	**20b**, 85	
	2d[b]	24	**20c**, 65	
	2e[b]	24	**20d**, 89	
PhCH=CHI (**19b**, >99/1)	**2a**[c]	28	**20a**, 72	>99/1
$Ph(CH_3)C$=CHI (**19c**, 98/2)	**2a**[b]	20	**20e**, 93	99/1
	2b	16	**20f**, 86	
n-C_5H_{11}CH=CHI (**19d**, 96/4)	**2a**	5	**20g**, 92	98/2
(9/91)	**2a**	7	**20g**, 82	10/90
n-C_6H_{13}CH=CHI (**19e**, 84/16)	**2a**[c]	10	**20h**, 96	84/16
	2b	5	**20i**, 86	
i-C_3H_7CH=CHI (**19f**, 97/3)	**2a**	14	**20j**, 73	97/3

[a] The reaction of **19** (1.0–3.0 mmol) with **2** (1.0–3.0 mmol) was carried out in DMF (with **2a**) or DMSO (with **2b**) at 120 °C under N_2 unless otherwise noted; [**19**]:[**2**]:[CuI]:[PPh_3]:[K_2CO_3] = 1:1: 0.05:0.1:1.5. [b] [CuI] = 0.1. [c] Reaction at 80 °C.

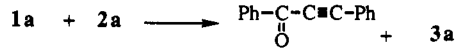
formation of **15**. In the case of 2-iodophenol (**1m**), a mixture of 2-phenylbenzofuran (**16**) (18%), phenol (**17**) (15%), and **4** (15%) was obtained, and benzofuran **16** (54%) was isolated from the reaction of 1-acetoxy-2-iodobenzene (**1n**). 2-Iodoaniline (**1o**) did not undergo the analogous cyclization and gave 2-amino-2-(phenylethynyl)-benzene (**18**) selectively.


19 2 20 (2)

Reaction of Vinyl Halides 19 with Terminal Alkynes 2. (*E*)-*β*-Bromostyrene (**19a**) smoothly reacted with alkynes **2a,b,d,e** to give the corresponding enyne compounds **20a-d** in good yields, irrespective of the alkynes employed (eq 2 and Table VI). As expected, (*E*)-*β*-iodostyrene (**19b**) was more reactive than **19a**, and the reaction could be completed at 80 °C. The reaction of other vinyl iodides **19c-f** with **2a** or **2b** also gave enynes **20e-j**. In each case, the *E*/*Z* ratio of the products was almost the same as the corresponding vinyl halides employed. The reaction of (*E*)- and (*Z*)-**19d** may also be representative, demonstrating that the coupling reaction proceeds with retention of the vinyl halide configuration. The reaction of (*Z*)-4-iodo-4-octene and methyl (*Z*)-3-bromo-2-propenoate with **2a** did not give the expected products.

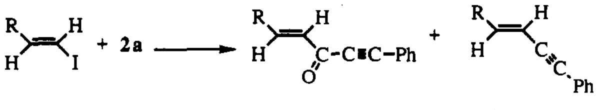
To investigate the relative reactivity differences between (*E*)- and (*Z*)-isomers, the reaction of a mixture of (*E*)- and (*Z*)-**19d** (*E*/*Z* = 50:50) with **2a** in DMF at 120 °C was followed by GLC (Figure 1). The (*E*)-isomer was consumed within 1 h, giving (*E*)-**20g** in 50% yield, whereas consumption of the (*Z*)-isomer required 7 h and gave (*Z*)-**20g** in 47% yield. This indicates that the (*E*)-isomer is more reactive than the (*Z*)-isomer and suggests that the reaction of vinyl halides is susceptible to steric effects.

Reaction of 1a or 19 with 2a under Carbon Monoxide. When the reaction of **1a** with **2a** in the presence of CuI and PPh_3 (PPh_3/CuI = 2.0) in DMF was carried out at 120 °C under a normal pressure of carbon monoxide, the alkyne **3a** was formed as the single product, as was observed for the analogous reaction under a nitrogen atmosphere (eq 3 and Table VII). Interestingly, a decrease in the amount of PPh_3 added (PPh_3/CuI = 0.5) induced formation of 1,3-diphenyl-1-propyn-3-one (**21**) (12%).[14] In addition, *N,N*-dimethyl-2-imidazolidinone (DMI) in place of DMF was found to increase the ratio of **21** to **3a** in a small but meaningful extent, whereas the carbon monoxide incorporation reaction did not occur in DMSO. A further decrease in the PPh_3/CuI ratio to 0.125 in the reaction in DMI resulted in the formation of **21** in a comparable amount to **3a**. The presence of PPh_3 was, however, essential for the reaction to proceed smoothly. The reaction of (*E*)-*β*-iodostyrene (**19b**) with **2a** also afforded 1,5-diphenyl-4-en-1-yn-3-one (**22b**) (46%) together with **20a** (22%) (eq 4); however, the reactions of (*E*)-**19d** with **2a** and **1a** with **2b** gave no carbonylation products.



$$\mathbf{1a} + \mathbf{2a} \longrightarrow \text{Ph}-\underset{\overset{\|}{\text{O}}}{\text{C}}-\text{C}\equiv\text{C}-\text{Ph} + \mathbf{3a} \qquad (3)$$

21


(4)

19b; R=Ph
19d; R=*n*-C_5H_{11}

22; 46%
0%

20a; 22%
20g; 85%

Reaction Scheme. The present reaction seems to involve initial formation of a copper(I) acetylide species: It was confirmed that treatment of **2a** (1.0 mmol) with CuI (0.5 mmol) in the presence of K_2CO_3 (1.5 mmol) in DMF at room temperature for 1 h gave copper(I) phen-

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(14) Copper-catalyzed cyclocarbonylation of *ortho*-substituted aryl iodides under pressurized carbon monoxide has recently been reported. Negishi, E.; Zhang, Y.; Shimoyama, I.; Wu, G. *J. Chem. Soc.* **1989**, *111*, 8018.

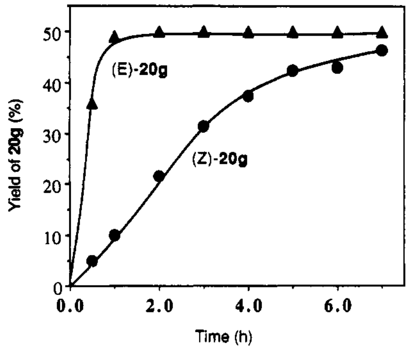


Figure 1. Time course of reaction of **19d** (E/Z = 50/50) with **2a** under N_2 at 120 °C: (*E*)-**20g**, ▲; (*Z*)-**20g**, ●.

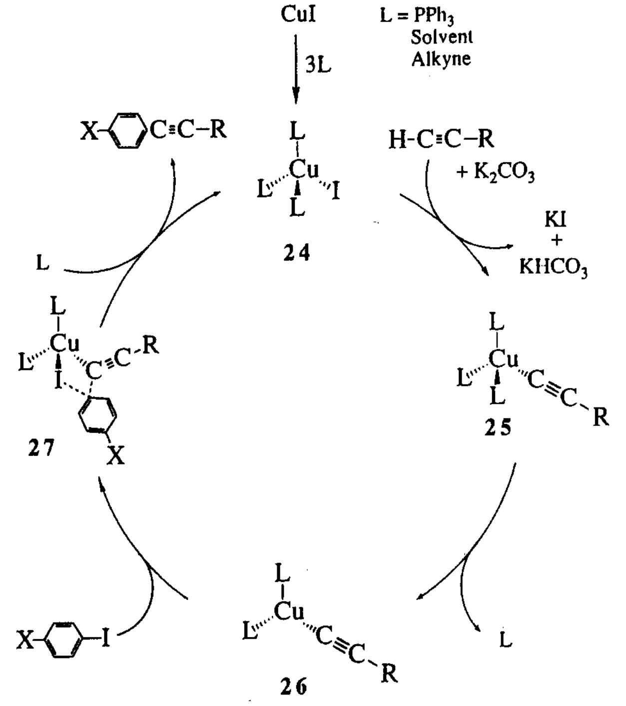
Table VII. Reaction of 1a with 2a under Carbon Monoxide[a]

solvent	PPh_3/CuI	yield[b] (%) 21	yield[b] (%) 3a	recov of **1a**[b] (%)
DMF	2.0	tr	76	0
DMF	0.5	12	83	0
DMSO	0.5	tr	88	3
DMI[c]	0.5	23	69	4
DMI	0.125	33	43	10
DMI[d]	0.125	17	20	49
DMI		tr	13	55
DMAc[e]	0.125	24	55	20

[a] Reaction conditions: **1a** (2.0 mmol), **2a** (2.0 mmol), CuI (0.1 mmol), K_2CO_3 (3.0 mmol), solvent (6 mL), 120 °C, CO (1 atm), 20 h. [b] Determined by GLC analysis. [c] DMI = 1,3-dimethyl-2-imidazolidinone. [d] CO (10 atm). [e] DMAc = *N,N*-dimethylacetamide.

ylacetylide (**23**) almost quantitatively (based on CuI used). The reaction of **1a** (3.0 mmol) with **23** (0.5 mmol) in DMF at 120 °C for 5 h afforded **3a** in a yield of 20% based on **23** used, whereas the coupling product was quantitatively formed within 2 h in the presence of PPh_3 (PPh_3/**23** = 2.0). It is known that the copper acetylide **23** is polymeric by nature and is almost insoluble in usual organic solvents.[15] The acetylide **23** could not be completely solubilized in DMF even by addition of PPh_3 (PPh_3/**23** = 2.0) at 120 °C. In contrast, no precipitation of copper acetylides was observed under the present catalytic conditions throughout the reaction. Thus, it may be reasonable to consider that PPh_3 coordinates to a copper(I) species employed and the reaction of the resulting copper–phosphine complex with an alkyne to give a soluble monomeric copper(I) acetylide. On the basis of these results, a possible mechanism for the present catalytic reaction is illustrated in Scheme I, where L represents neutral ligands such as PPh_3, solvent, and alkyne. The reaction of copper acetylide intermediate **25** generated in situ from CuI, PPh_3, and terminal alkyne with aryl iodide via a four-centered transition state **27**, as has been proposed for the Castro reaction,[2a] may give coupling product, regenerating copper(I) complex **24**.[16] The electron-donating property of PPh_3 may also enhance the reaction in the transition state **27**. The fact that phosphine ligands having more electron-donating ability than with PPh_3 were ineffective led us to deduce that the formation of a coordinatively unsaturated intermediate **26** is also an important process, which is retarded by the presence of them. It should be noted that copper-assisted nucleophilic substitution reactions of aryl halides are known to be generally suppressed by an excess of ligands.[8]

Scheme I



On the other hand, treatment of **1a** with **20** in the presence of 0.125 equiv of PPh_3 to **23** under carbon monoxide resulted in the exclusive formation of **3a** with no carbonylation product being detected. This suggests that the reaction sequence leading to **19** may involve intermediate(s) other than those indicated in Scheme I, such as a phenylcopper species, which reacts with carbon monoxide.[18]

Experimental Section

^{1}H-NMR spectra were recorded at 400 MHz for $CDCl_3$ solutions. MS data were obtained by EI. Aryl iodides **1e**,[19] **1f**,[20] **1g**,[20] **1l**,[21] **1m**,[22] and **1n**[23] and alkynes **2d**,[24] **2e**,[25] **2f**,[26] and **2g**[24] were prepared by the methods reported previously. Vinyl halides (*E*)-**19a**,[27] (*E*)-**19b**,[27,28] **19c** (E/Z = 98/2),[28,29] **19d** (E/Z = 96/4),[30] **19d** (E/Z = 9/91),[28,31] **19e** (E/Z = 86/16),[32] and **19f** (E/Z = 97/3)[32] were also prepared according to published procedures. Other starting materials were commercially available. Solvents were purified by standard methods before use. The experimental details given below may be regarded as typical in methodology and scale.

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(16) An attempt to isolate a complex which corresponds to **25** was also made. Treatment of **2a** with an equimolar amount of $CuBr(PPh_3)_3$[17] in the presence of K_2CO_3 in DMF at 80 °C for 3 h under nitrogen followed by addition of water gave a yellow precipitate. The FT-IR spectrum of the solid showed a characteristic peak for a carbon–carbon triple bond at 2045 cm^{-1}. Its X-ray fluorescence spectrum indicated that it contains copper and phosphorus atoms. Heating it (ca. 500 mg) with iodobenzene (**1a**) (204 mg, 1.0 mmol) in DMF at 120 °C for 1 h gave **3a** (0.5 mmol). These results suggest that the solid may be an equivalent of **25**. However, purification and further characterization were unsuccessful because of its labile nature.

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Reaction of Iodobenzene (1a) with Phenylacetylene (2a). To a mixture of copper(I) iodide (0.25 mmol), triphenylphosphine (0.5 mmol), potassium carbonate (7.5 mmol), and DMF (10 mL) were added **1a** (5.0 mmol) and **2a** (5.0 mmol) under nitrogen. The resulting mixture was stirred at 120 °C for 16 h after which it was poured into water, extracted with ether, and dried over sodium sulfate. Product **3a** (873 mg, 98%) was isolated by column chromatography on silica gel using hexane as eluant and was identified by comparison with an authentic sample.

1-Phenyl-1-heptyne (3b):[33] oil; ^{1}H NMR δ 0.92 (t, 3 H, J = 7.3 Hz), 1.31–1.47 (m, 4 H), 1.61 (tt, 2 H, J = 7.3, 7.3 Hz), 2.39 (t, 2 H, J = 7.3 Hz), 7.23–7.28 (m, 3 H), 7.37–7.40 (m, 2 H); MS m/z 172 (M$^+$).

2-[(3-Phenyl-2-propynyl)oxy]-3,4,5,6-tetrahydro-2*H*-pyran (3d):[34] oil; ^{1}H NMR δ 1.53–1.88 (m, 6 H), 3.54–3.59 (m, 1 H), 3.87–3.92 (m, 1 H), 4.44–4.54 (m, 2 H), 4.91 (t, 1 H, J = 3.4 Hz), 7.28–7.32 (m, 3 H), 7.44–7.46 (m, 2 H); MS m/z 216 (M$^+$).

1-Phenyl-3-(*tert*-butoxy)-1-propyne (3e): oil; ^{1}H NMR δ 1.29 (s, 9 H), 4.31 (s, 2 H), 7.26–7.30 (m, 3 H), 7.43–7.45 (m, 2 H); MS m/z 188 (M$^+$). Anal. Calcd for $C_{13}H_{16}O$: C, 82.92; H, 8.58. Found: C, 83.07; H, 8.42.

1-Phenyl-3-acetoxy-1-propyne (3f):[35] oil; ^{1}H NMR δ 2.04 (s, 3 H), 4.82 (s, 2 H), 7.22–7.23 (m, 3 H), 7.36–7.38 (m, 2 H); MS m/z 174 (M$^+$).

2-[(3-Phenyl-1,1-dimethyl-2-propynyl)oxy]-3,4,5,6-tetrahydro-2*H*-pyran (3g): oil; ^{1}H NMR δ 1.59 (s, 3 H), 1.63 (s, 3 H), 1.72–1.87 (m, 6 H), 3.50–3.55 (m, 1 H), 3.96–4.01 (m, 1 H), 5.15 (dd, 1 H, J = 2.9, 5.4 Hz), 7.28–7.30 (m, 3 H), 7.40–7.43 (m, 2 H); MS m/z 244 (M$^+$). Anal. Calcd for $C_{16}H_{20}O_2$: C, 78.64; H, 8.27. Found: C, 78.64; H, 8.27.

1-Nitro-4-(phenylethynyl)benzene (5): mp 118–120 °C (from hexane–benzene) (lit.[2b] mp 119–120 °C); ^{1}H NMR δ 7.38–7.40 (m, 4 H), 7.55–7.57 (m, 2 H), 7.65–7.68 (m, 2 H), 8.21–8.23 (m, 2 H); MS m/z 223 (M$^+$).

1-Chloro-4-(phenylethynyl)benzene (6): mp 79.5–81.5 °C (from hexane) (lit.[36] mp 81.5–82 °C); ^{1}H NMR δ 7.30–7.36 (m, 5 H), 7.43–7.47 (m, 2 H), 7.51–7.53 (m, 2 H); MS m/z 212 (M$^+$).

1-(4-Chlorophenyl)-1-heptyne (7):[37] oil; ^{1}H NMR δ 0.92 (t, 3 H, J = 7.3), 1.32–1.44 (m, 4 H), 1.60 (tt, 2 H, J = 7.3, 7.3 Hz), 2.38 (t, 2 H, J = 7.3), 7.22–7.25 (m, 2 H), 7.29–7.32 (m, 2 H); MS m/z 206 (M$^+$).

1-Methyl-4-(phenylethynyl)benzene (8): mp 68–69 °C (from hexane) (lit.[38] mp 72–74 °C); ^{1}H NMR δ 2.36 (s, 3 H), 7.15 (d, 2 H, J = 7.8 Hz), 7.32–7.34 (m, 3 H), 7.41–7.43 (m, 2 H), 7.51–7.53 (m, 2 H); MS m/z 192 (M$^+$).

1-(4-Methylphenyl)-1-heptyne (9):[37] oil; ^{1}H NMR δ 0.92 (t, 3 H, J = 7.3 Hz), 1.32–1.46 (m, 4 H), 1.56–1.73 (tt, 2 H, J = 7.3, 7.3 Hz), 2.31 (s, 3 H), 2.38 (t, 2 H, J = 7.3 Hz), 7.07 (d, 2 H, J = 8.1 Hz), 7.28 (d, 2 H, J = 8.1 Hz); MS m/z 186 (M$^+$).

1-Methoxy-2-(phenylethynyl)benzene (10):[2b] oil; ^{1}H NMR δ 3.90 (s, 3 H), 6.88–6.95 (m, 2 H), 7.29–7.35 (m, 4 H), 7.48–7.51 (m, 1 H), 7.54–7.57 (m, 2 H); MS m/z 208 (M$^+$).

1-(Phenylethynyl)naphthalene (11):[39] oil; ^{1}H NMR δ 7.33–7.44 (m, 3 H), 7.48–7.52 (m, 1 H), 7.55–7.60 (m, 2 H), 7.63–7.65 (m, 2 H), 7.74–7.84 (m, 3 H), 8.43–8.45 (d, 1 H); MS m/z 228 (M$^+$).

2-(Phenylethynyl)naphthalene (12): mp 114–115 °C (lit.[39] mp 117 °C); ^{1}H NMR δ 7.34–7.38 (m, 3 H), 7.48–7.50 (m, 2 H), 7.57–7.59 (m, 3 H), 7.80–7.83 (m, 3 H), 8.06 (s, 1 H); MS m/z 228 (M$^+$).

1-Nitro-2-(phenylethynyl)benzene (13):[2b] oil; ^{1}H NMR δ 7.36–7.39 (m, 3 H), 7.43–7.47 (m, 1 H), 7.57–7.60 (m, 3 H), 7.69–7.72 (m, 1 H), 8.05–8.08 (m, 1 H); MS m/z 223 (M$^+$).

3-Phenylisocoumarin (14): mp 89–90 °C (from hexane–benzene) (lit.[40] mp 88 °C); ^{1}H NMR δ 6.96 (s, 1 H), 7.43–7.52 (m, 5 H), 7.70–7.74 (m, 1 H), 7.88–7.90 (m, 2 H), 8.31–8.33 (m, 1 H); MS m/z 222 (M$^+$).

Methyl 2-(phenylethynyl)benzoate (15):[41] oil; ^{1}H NMR δ 3.97 (s, 3 H), 7.34–7.40 (m, 4 H), 7.47–7.52 (m, 1 H), 7.57–7.59 (m, 2 H), 7.64–7.66 (m, 1 H), 7.97–7.99 (m, 1 H); MS m/z 236 (M$^+$).

2-Phenylbenzofuran (16): mp 118 °C (lit.[2c] mp 120–121 °C); ^{1}H NMR δ 7.03 (s, 1 H), 7.21–7.35 (m, 2 H), 7.35–7.37 (m, 1 H), 7.43–7.47 (m, 2 H), 7.51–7.53 (m, 1 H), 7.57–7.60 (m, 1 H), 7.86–7.88 (m, 2 H); MS m/z 194 (M$^+$).

1-Amino-2-(phenylethynyl)benzene (18): mp 92–93 °C (from hexane) (lit.[2c] mp 91–92 °C); ^{1}H NMR δ 4.27 (s, 2 H), 6.70–6.74 (m, 2 H), 7.12–7.16 (m, 1 H), 7.33–7.47 (m, 4 H), 7.51–7.55 (m, 2 H); MS m/z 193 (M$^+$).

(*E*)-1,4-Diphenyl-3-buten-1-yne (20a): mp 96–97 °C (from hexane) (lit.[3c] mp 97–98 °C); ^{1}H NMR δ 6.39 (d, 1 H, J = 16.4 Hz), 7.04 (d, 1 H, J = 16.4 Hz), 7.25–7.49 (m, 10 H); MS m/z 204 (M$^+$).

(*E*)-1-Phenyl-1-nonen-3-yne (20b):[42] oil; ^{1}H NMR δ 0.92 (t, 3 H, J = 7.3 Hz), 1.30–1.44 (m, 4 H), 1.56 (tt, 2 H, J = 7.3, 7.3 Hz), 2.34 (dt, 2 H, J = 7.3, 2.0 Hz), 6.15 (dt, 1 H, J = 16.6, 2.0 Hz), 6.86 (d, 1 H, J = 16.6 Hz), 7.24–7.36 (m, 5 H); MS m/z 198 (M$^+$).

(*E*)-2-[(5-Phenyl-4-penten-2-ynyl)oxy]-3,4,5,6-tetrahydro-2*H*-pyran (20c): oil; ^{1}H NMR δ 1.50–1.86 (m, 6 H), 3.55–3.58 (m, 1 H), 3.85–3.90 (m, 1 H), 4.38–4.50 (m, 2 H), 4.86 (t, 1 H, J = 3.4 Hz), 6.15–6.20 (m, 1 H), 6.97 (d, 1 H, J = 16.1 Hz), 7.28–7.35 (m, 5 H); MS m/z 242 (M$^+$). A mixture of **20c** (120 mg, 0.5 mmol), *p*-toluenesulfonic acid (50 mg), and THF (5 mL) was stirred at rt for 24 h. The resulting solution was poured into water, extracted with ether, and dried over sodium sulfate. (*E*)-5-Phenyl-4-penten-2-yn-1-ol (65 mg, 83%) was isolated by column chromatography on silica gel using hexane–ether (9:1) as eluant:[3c] oil; ^{1}H NMR δ 1.78 (s, 1 H), 4.37 (d, 2 H, J = 2.0 Hz), 6.10 (dt, 2 H, J = 16.1, 2.0 Hz), 6.89 (d, 2 H, J = 16.1 Hz), 7.22–7.31 (m, 5 H); MS m/z 158 (M$^+$).

(*E*)-1-(*tert*-Butoxy)-5-phenyl-4-penten-2-yne (20d): oil; ^{1}H NMR δ 1.27 (s, 9 H), 4.26 (d, 2 H, J = 2.0 Hz), 6.14–6.19 (m, 1 H), 6.94 (d, 1 H, J = 16.6 Hz), 7.25–7.37 (m, 5 H); MS m/z 214 (M$^+$). A mixture of **20d** (99 mg, 0.5 mmol), trifluoroacetic acid (0.1 mL), and THF (5 mL) was stirred at rt for 20 h. The resulting solution was poured into water, extracted with ether, and dried over sodium sulfate. (*E*)-5-Phenyl-4-penten-2-yn-1-ol (62 mg, 79%) was isolated by column chromatography on silica gel using hexane–ether (9:1) as eluant.

(*E*)-1,4-Diphenyl-3-penten-1-yne (20e): mp 88–89 °C (from hexane); ^{1}H NMR δ 2.45 (s, 3 H), 6.12 (s, 1 H), 7.30–7.36 (m, 6 H), 7.45–7.49 (m, 4 H); MS m/z 218 (M$^+$). Anal. Calcd for $C_{17}H_{14}$: C, 93.52; H, 6.48. Found: C, 93.24; H, 6.34.

(*E*)-2-Phenyl-2-decen-4-yne (20f): oil; 145–150 °C/2 mmHg; ^{1}H NMR δ 0.92 (t, 3 H, J = 7.3 Hz), 1.32–1.46 (m, 4 H), 1.59 (dd, 2 H, J = 7.3, 7.3 Hz), 2.28 (s, 3 H), 2.41 (td, 2 H, J = 7.3, 2.0 Hz), 5.87 (dd, 1 H, J = 1.0, 2.4 Hz), 7.24–7.32 (m, 3 H), 7.39–7.42 (m, 2 H); MS m/z 212 (M$^+$). Anal. Calcd for $C_{16}H_{20}$: C, 90.06; H, 9.47. Found: C, 90.47; H, 9.58.

1-Phenyl-3-octen-1-yne (20g): oil; ^{1}H NMR (*E*) δ 0.90 (t, 3 H, J = 7.3 Hz), 1.28–1.34 (m, 4 H), 1.39–1.53 (m, 2 H), 1.42 (tt, 2 H, J = 7.3, 7.3 Hz), 2.15 (dtd, 2 H, J = 7.3, 7.3, 1.5 Hz), 5.68

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(dt, 1 H, *J* = 15.6, 1.5 Hz), 6.24 (dt, 1 H, *J* = 15.6, 7.3 Hz), 7.26–7.30 (m, 3 H), 7.40–7.43 (m, 2 H); (*Z*) δ 0.90 (t, 3 H, *J* = 7.3 Hz), 1.30–1.36 (m, 4 H), 1.42–1.47 (m, 2 H), 2.39 (tdd, 2 H, *J* = 7.3, 7.3, 1.5 Hz), 5.66 (dt, 1 H, *J* = 10.7, 1.5 Hz), 5.96 (dt, 1 H, *J* = 10.7, 7.3 Hz), 7.26–7.30 (m, 3 H), 7.41–7.44 (m, 2 H); MS *m/z* 198 (M^+). Anal. Calcd for $C_{15}H_{18}$: C, 90.83; H, 9.17. Found: C, 90.89; H, 9.22.

1-Phenyl-3-decen-1-yne (20h):[6] oil; ^{1}H NMR (*E*) δ 0.88 (t, 3 H, *J* = 7.3 Hz), 1.25–1.47 (m, 8 H), 2.16 (ddt, 2 H, *J* = 7.3, 1.5, 7.3 Hz), 5.69 (dt, 1 H, *J* = 16.0, 1.5 Hz), 6.24 (dt, 1 H, *J* = 16.0, 7.3 Hz), 7.25–7.31 (m, 3 H), 7.40–7.43 (m, 2 H); (*Z*) δ 0.88 (t, 3 H, *J* = 7.3 Hz), 1.25–1.47 (m, 8 H), 2.40 (ddt, 2 H, *J* = 7.3, 1.5, 7.5 Hz), 5.69 (dt, 1 H, *J* = 10.7, 1.5 Hz), 5.98 (dt, 1 H, *J* = 10.7 Hz, 7.3 Hz), 7.25–7.31 (m, 3 H), 7.30–7.43 (m, 2 H); MS *m/z* 212 (M^+).

8-Pentadecen-6-yne (20i): oil; ^{1}H NMR δ 0.86 (m, 6 H), 1.22–1.43 (m, 12 H), 1.52 (tt, 2 H, *J* = 7.3, 7.3 Hz), 2.07 (dd, 2 H, *J* = 7.3, 7.3 Hz), 2.22–2.29 (m, 1 H), 6.01–6.08 (m, 1 H); MS *m/z* 206 (M^+). Anal. Calcd for $C_{15}H_{24}$: C, 87.30; H, 12.70. Found: C, 87.31; H, 12.86.

1-Phenyl-5-methyl-hex-1-yn-3-ene (20j): oil; ^{1}H NMR δ 1.05 (d, 6 H, *J* = 6.8 Hz), 2.41 (sep,dd, 1 H, *J* = 6.8, 6.8, 1.5 Hz), 5.66 (dd, 1 H, *J* = 16.1, 1.5 Hz), 6.23 (dd, 1 H, *J* = 16.1, 6.8 Hz), 7.26–7.30 (m, 3 H), 7.40–7.43 (m, 2 H); MS *m/z* 170 (M^+). Anal. Calcd for $C_{13}H_{14}$: C, 91.71; H, 8.29. Found: C, 91.46; H, 8.32.

Reaction of 1a with CuI. A mixture of CuI (95 mg, 0.5 mmol), **1a** (102 mg, 1.0 mmol), and K_2CO_3 (207 mg, 1.5 mmol) in DMF (10 mL) was stirred at rt for 30 min under nitrogen, and then water (20 mL) was added. A yellow solid (81 mg) thus precipitated was collected by filtration and washed with water, ethanol, and ether. The solid was identified as copper(I) phenylacetylide (**23**) by comparison of its FT-IR spectrum with that of an authentic sample.[2b]

Reaction of 1a with 2a under Carbon Monoxide. Iodobenzene (**1a**) (2.0 mmol) and phenylacetylene (**2a**) (2.0 mmol) were added to a mixture of copper(I) iodide (0.1 mmol), triphenylphosphine (1.25 μmol), potassium carbonate (3.0 mmol), and DMI (4 mL) under carbon monoxide. The resulting mixture was stirred at 120 °C for 24 h after which it was poured into water, extracted with water, and dried over sodium sulfate. Product **21** (114 mg, 28%) was isolated by column chromatography on silica gel using hexane–ether (8:1) as eluant: oil;[43] ^{1}H NMR δ 7.37–7.52 (m, 6 H), 7.58–7.68 (m, 4 H); MS *m/z* 206 (M^+).

1,5-Diphenyl-4-penten-1-yn-3-one (22): mp 73–75 °C (from hexane) (lit.[43] mp 7.34–74 °C); ^{1}H NMR δ 6.88 (d, 1 H, *J* = 15.6 Hz) 7.40–7.50 (m, 6 H), 7.58–7.67 (m, 4 H), 7.92 (d, 1 H, *J* = 15.6 Hz); MS *m/z* 232 (M^+).

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