Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron
Tetrahedron 63 (2007) 1963–1969

# Cyclopalladated ferrocenylimines: efficient catalysts for homocoupling and Sonogashira reaction of terminal alkynes

Fan Yang,[a,b] Xiuling Cui,[a,b] Ya-nan Li,[a,b] Jinli Zhang,[a,b] Ge-rui Ren[a,b] and Yangjie Wu[a,b,*]

[a]*Chemistry Department, The Key Laboratory of Chemical Biology and Organic Chemistry of Henan Province, Zhengzhou University, Zhengzhou 450052, PR China*
[b]*The Key and Open Laboratory of Applied Chemistry of Henan Universities, Zhengzhou University, Zhengzhou 450052, PR China*

Received 10 October 2006; revised 20 December 2006; accepted 21 December 2006
Available online 27 December 2006

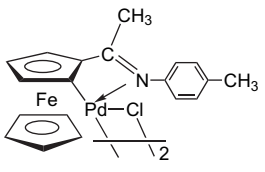
**Abstract**—A novel pathway for homocoupling of terminal alkynes has been described using cyclopalladated ferrocenylimine **1** or **2**/CuI as catalyst in the air. This catalytic system could tolerate several functional groups. The palladacycle **2** in the presence of *n*-$Bu_4NBr$ as an additive could be applied to Sonogashira cross-coupling reaction of aryl iodides, aryl bromides, and some activated aryl chlorides with terminal alkynes under amine- and copper-free conditions, mostly to give moderate to excellent yields.


## 1. Introduction

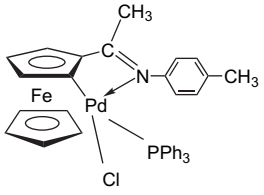
Alkynes are important skeleton in some natural products, pharmaceuticals, biologically active molecules, and nonlinear optical materials.[1,2] Of the various approaches to synthesize symmetrical diynes and substituted alkynes, palladium-catalyzed homocoupling and Sonogashira cross-coupling of terminal alkynes are two of the most efficient routes.[3–10] A number of catalytic systems has been developed.[6–9] For the successful palladium-catalyzed homocoupling of terminal alkynes, an oxidant is necessary besides phosphine ligands, CuI and the additive such as TBAB as described in detail by Fairlamb and co-workers.[7] To satisfy the environmental concerns, $O_2$ is an evidently more attractive alternative to the reported oxidants. So palladium-catalyzed homocoupling of terminal alkynes performed in the air is extremely significant. Palladium-catalyzed Sonogashira reaction is typically catalyzed by palladium complexes in the presence of a copper salt as cocatalyst and an amine as base.[8] CuI is generally employed as the cocatalyst, which can result in Cu(I) acetylides in situ and induce the homocoupling.[10] Therefore Sonogashira reaction catalyzed by palladium complexes without amines and copper salts has attracted more and more attentions recently.[9]

On the other hand, cyclopalladated complexes emerging as a new family of palladium catalysts have been widely used in carbon–carbon and carbon–heteroatom bond formation.[11] Only oxime-derived palladacycles catalyzed homocoupling of terminal alkynes were reported recently.[12] This coupling reaction was effective for both aromatic and aliphatic alkynes. However, for alkynes with hydroxyl group, the expected product was obtained in low yield (25%). The catalytic systems for Sonogashira reaction catalyzed by palladacycles had also been reported.[12,13] For example, oxime-derived palladacycles are quite effective for aryl iodides and bromides with phenylacetylene or other alkynes.[12] Very recently, Dupont and co-workers have also described a new type of palladacycles. The substrates could be iodoarenes and activated bromoarenes.[13] However, both of the two catalytic systems are limited to aryl iodides and bromides. So a new system for the Sonogashira cross-coupling reaction of a wide range of aryl halides using palladacycle as the catalyst should be developed.

Here we would like to report cyclopalladated ferrocenylimine **1** or **2** in the presence of CuI as an efficient, mild, and air stable catalytic system for the synthesis of diynes via dimerization of terminal alkynes bearing several functional groups, and palladacycle **2** as the catalyst with *n*-$Bu_4NBr$ in Sonogashira cross-coupling reaction of ArX (X=I, Br, and Cl) with terminal alkynes under amine- and copper-free conditions.[14]



1



2

*Keywords*: Cyclopalladated ferrocenylimine; Homocoupling; Sonogashira reaction; Terminal alkynes.
* Corresponding author. Tel./fax: +86 371 67766667; e-mail: wyj@zzu.edu.cn

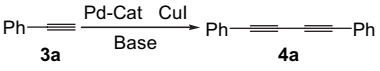
0040–4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2006.12.064

## 2. Results and discussion

### 2.1. Palladium-catalyzed homocoupling of terminal alkynes

The results for the screening of the reaction conditions to promote the catalytic homocoupling of phenylacetylene are shown in Table 1. It showed that DMF was the best solvent (entries 1–5), palladacycle **2** was more active than catalyst **1** (entries 6 and 7). Even with 0.1 mol % of **2**, the expected product was formed in 95% yield within 10 h (entry 8). If the loading of catalyst **2** was reduced to 0.01 mol %, only 55% yield was obtained after 24 h (entry 9). In the absence of the palladacycle, the reaction proceeded slowly (24 h) with low yield (20%, entry 10) and only moderate yield (57%) was obtained without CuI (entry 11).

**Table 1**. Palladium-catalyzed homocoupling of phenylacetylene[a]




| Entry | Solvent | Cat | Cat (mol %) | $t$ (h) | $T$ (°C) | Yield[b] (%) |
|---|---|---|---|---|---|---|
| 1 | DMSO | **1** | 0.5 | 4 | 50 | 20 |
| 2 | $CH_3CN$ | **1** | 1 | 6 | 50 | 36 |
| 3 | $CH_3CN$ | **1** | 1 | 29 | rt | 25 |
| 4 | $CH_3CN$ | **1** | 0.5 | 45 | rt | 79 |
| 5 | DMF | **1** | 0.5 | 45 | rt | 95 |
| 6 | DMF | **1** | 1 | 7 | 40 | 85 |
| 7 | DMF | **2** | 1 | 2 | 40 | 96 |
| 8 | DMF | **2** | 0.1 | 10 | 40 | 95 |
| 9 | DMF | **2** | 0.01 | 24 | 40 | 55 |
| 10[c] | DMF | — | 0 | 24 | 40 | 20 |
| 11[d] | DMF | **2** | 1 | 24 | 40 | 57 |

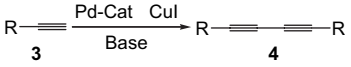
[a] Reaction conditions: **3a** (1 mmol), palladacycle, CuI (2.5 mol %), KOAc (1.5 equiv), and solvent (2.5 mL) in the air.
[b] Isolated yields.
[c] Without palladacycle.
[d] In the absence of CuI.

Under these optimized conditions, we examined the substrate scope. As shown in Table 2, this catalytic system could be used for homocoupling of various terminal alkynes. For the aromatic or heterocyclic aromatic alkynes, both **1** and **2** gave almost similar results (entries 1–4). While for aliphatic alkynes, the catalytic activity of **2** was higher than that of **1** (entries 5–9). For hydroxyl (**3f** and **g**) or ester (**3h**) containing alkynes (entries 10, 12, and 14), only lower yields (42%, 61%, 52%, respectively) were obtained. It is notable that when the base and solvent were *i*-$Pr_2EtN$ and THF (entries 11, 13, and 15), moderate to good yields (92%, 89%, 71%, respectively) were obtained.

### 2.2. Palladium-catalyzed Sonogashira cross-coupling reaction of aryl halides with terminal alkynes

Initially, palladacycle-catalyzed Sonogashira reaction of PhI (**5a**) with phenylacetylene (**3a**) was investigated to survey the optimal conditions. As shown in Table 3, with 1 mol % of palladacycle **2** the best result was obtained using KOAc as base, *n*-$Bu_4NBr$ as an additive in DMA under nitrogen atmosphere (entry 7). The catalytic activity was also examined (entries 7–10). The catalyst loadings could be decreased from 1 mol % to 0.01 mol %, and moderate yield (77%) could be obtained after prolonging to 24 h (entry 9).

**Table 2**. Palladium-catalyzed homocoupling of alkynes[a]



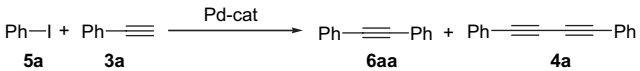

| Entry | Alkyne | Cat | Cat (mol %) | $t$ (h) | Product No. | Product Yield[b] (%) |
|---|---|---|---|---|---|---|
| 1 | $n$-$C_5H_{11}$—≡—(**3b**) | **1** | 1 | 17 | **4b** | 94 |
| 2 | **3b** | **2** | 1 | 28 | **4b** | 95 |
| 3 | N, —≡—(**3c**) | **1** | 1 | 30 | **4c** | 70 |
| 4 | **3c** | **2** | 1 | 25 | **4c** | 75 |
| 5 | $CH_3(CH_2)_4C{\equiv}CH$ (**3d**) | **1** | 1 | 20 | **4d** | 50 |
| 6 | **3d** | **2** | 1 | 20 | **4d** | 88 |
| 7 | **3d** | **2** | 0.1 | 40 | **4d** | 87 |
| 8 | $CH_3(CH_2)_7C{\equiv}CH$ (**3e**) | **1** | 1 | 20 | **4e** | 61 |
| 9 | **3e** | **2** | 1 | 21 | **4e** | 82 |
| 10 | HO, —≡—(**3f**) | **2** | 1 | 40 | **4f** | 42 |
| 11[c] | **3f** | **2** | 1 | 26 | **4f** | 92 |
| 12 | OH, —≡—(**3g**) | **2** | 1 | 44 | **4g** | 61 |
| 13[c] | **3g** | **2** | 1 | 31 | **4g** | 89 |
| 14 | O, O, —≡—(**3h**) | **2** | 1 | 18 | **4h** | 52 |
| 15[c] | **3h** | **2** | 1 | 8 | **4h** | 71 |

[a] Reaction conditions: **3** (1 mmol), palladacycle, CuI (2.5 mol %), KOAc (1.5 equiv), and DMF (2.5 mL) at 40 °C in the air.
[b] Isolated yields.
[c] Reaction conditions: **3** (1 mmol), palladacycle, CuI (2.5 mol %), *i*-$Pr_2EtN$ (1.2 equiv), and THF (2.5 mL) at 40 °C in the air.

However, homocoupling product (**4a**) increased with decreased loading of the catalyst (entries 7–10).

Under the optimized reaction conditions, we first investigated the reactions of aryl iodides bearing electron-donating

**Table 3**. Sonogashira cross-coupling of PhI (**5a**) with phenylacetylene (**3a**)[a]



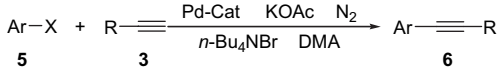

| Entry | Base/solvent | Additive | $t$ (h) | Cat (mol %) | Yield[b] (%) **6aa** | **6aa/4a** |
|---|---|---|---|---|---|---|
| 1 | KOAc/DMF | *n*-$Bu_4NBr$ | 3 | 1 | 34 | 1/1 |
| 2 | KOAc/DMA | —[c] | 1.5 | 1 | 41 | 3/1 |
| 3[d] | *i*-$Pr_2EtN$/THF | —[c] | 11 | 1 | 8 | 30/1 |
| 4 | $Cs_2CO_3$/DMA | *n*-$Bu_4NBr$ | 1 | 1 | 28 | 1.5/1 |
| 5 | KOAc/DMA | CuI | 1 | 1 | 64 | 4/1 |
| 6 | KOAc/DMA | *n*-$Bu_4NBr$ | 2 | 1 | 63 | 31/1 |
| 7[e] | KOAc/DMA | *n*-$Bu_4NBr$ | 3 | 1 | 90 | —[f] |
| 8[e] | KOAc/DMA | *n*-$Bu_4NBr$ | 8 | 0.1 | 88 | —[f] |
| 9[e] | KOAc/DMA | *n*-$Bu_4NBr$ | 24 | 0.01 | 77 | 10/1 |
| 10[e] | KOAc/DMA | *n*-$Bu_4NBr$ | 48 | 0.001 | 57 | 7/1 |

[a] Reaction conditions: PhI (0.5 mmol), phenylacetylene (0.6 mmol), base (0.75 mmol), *n*-$Bu_4NBr$ (0.75 mmol) or CuI (3 mol %), palladacycle **2**, and solvent (2.5 mL) at 80 °C.
[b] Isolated yields.
[c] No additives or CuI.
[d] *i*-$Pr_2EtN$ (2 equiv).
[e] Reactions under nitrogen atmosphere.
[f] No detectable butadiyne.

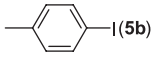
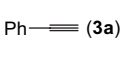
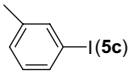
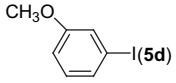
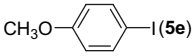
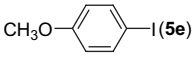
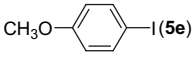
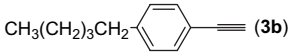
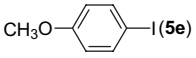
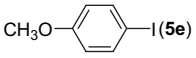
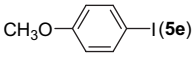
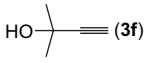
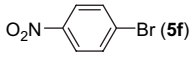
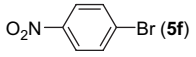
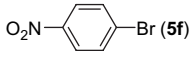
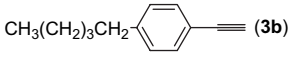
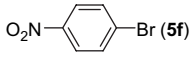
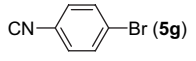
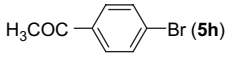
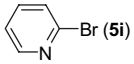
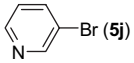
groups (**5b–e**) with various terminal alkynes. As shown in Table 4, Sonogashira reaction proceeded smoothly and moderate to excellent yields were obtained (entries 1–4). The reaction of *p*-iodoanisole with phenylacetylene gave only 56% yield with 0.01 mol % of palladacycle **2** (entry 5). The reaction of electron-rich *p*-iodoanisole with aromatic alkynes, aliphatic alkynes, and alkynes with hydroxyl group also gave moderate yields (entries 6–9).

The electron-poor, electron-neutral, and electron-rich aryl bromides as substrates were investigated (entries 10–23). The moderate to high yields were obtained for electron-poor aryl bromides (**5f–h**) (entries 10–15). It is notable that good to excellent yields were obtained for heteroaryl bromides (**5i–l**) (entries 16–19). However, for electron-neutral and electron-rich aryl bromides (**5m–p**), relatively lower to moderate yields were observed (entries 20–23).

**Table 4**. Sonogashira cross-coupling of ArX with terminal alkynes[a]

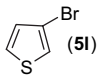
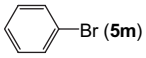
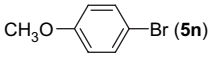
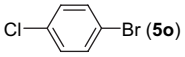
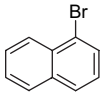
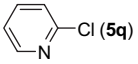
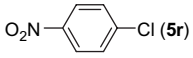
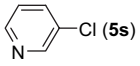
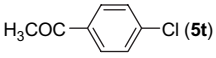



**5** **3** **6**

| Entry | ArX | R— | *t* (h) | Product | |
|---|---|---|---|---|---|
| | | | | No. | Yield[b] (%) |
| 1 |  |  | 5.5 | **6ba** | >99 |
| 2 |  |  | 5.5 | **6ca** | 75 |
| 3 |  |  | 5.5 | **6da** | 74 |
| 4 |  |  | 11 | **6ea** | 83 |
| 5[c] |  |  | 24 | **6ea** | 56 |
| 6 |  |  | 24 | **6eb** | 68 |
| 7 |  | 1-Hextyne (**3d**) | 21 | **6ed** | 74 |
| 8 |  | 1-Decyne (**3e**) | 23 | **6ee** | 80 |
| 9 |  |  | 24 | **6ef** | 61 |
| 10 |  |  | 6 | **6fa** | 91 |
| 11[d] |  |  | 10 | **6fa** | 93 |
| 12 |  |  | 24 | **6fb** | 90 |
| 13 |  | 1-Decyne (**3e**) | 24 | **6fe** | 63 |
| 14 |  |  | 10 | **6ga** | 93 |
| 15 |  |  | 24 | **6ha** | 77 |
| 16 |  |  | 20 | **6ia** | 99 |
| 17 |  |  | 20 | **6ja** | 96 |
| 18 |  |  | 20 | **6ka** | 83 |

(*continued*)

**Table 4**. (*continued*)

| Entry | ArX | R— | *t* (h) | Product | |
|---|---|---|---|---|---|
| | | | | No. | Yield[b] (%) |
| 19 |  (**5l**) | Ph— (**3a**) | 22 | **6la** | 85 |
| 20 |  (**5m**) | Ph— (**3a**) | 6.5 | **6aa** | 60 |
| 21 |  (**5n**) | Ph— (**3a**) | 20 | **6ea** | 42 |
| 22 |  (**5o**) | Ph— (**3a**) | 22 | **6ma** | 63 |
| 23 |  (**5p**) | Ph— (**3a**) | 22.5 | **6na** | 85 |
| 24[e] |  (**5q**) | Ph— (**3a**) | 24 | **6ia** | 87 |
| 25[e] |  (**5r**) | Ph— (**3a**) | 24 | **6fa** | 50 |
| 26[e] |  (**5s**) | Ph— (**3a**) | 24 | **6ja** | 29 |
| 27[e] |  (**5t**) | Ph— (**3a**) | 30 | **6ha** | 33 |

[a] Reaction conditions: ArX (0.5 mmol), alkyne (0.6 mmol), KOAc (0.75 mmol), *n*-$Bu_4NBr$ (0.75 mmol), palladacycle **2** (1 mol %), and DMA (2.5 mL) under nitrogen at 80 °C.
[b] Isolated yields.
[c] Palladacycle **2** (0.01 mol %).
[d] Palladacycle **2** (0.1 mol %).
[e] At 110 °C.

We also studied the coupling reaction of electron-poor aryl chlorides at higher temperature and observed that the substituted groups had a notable effect on the yields. For example, good (87%) and moderate (50%) yields were obtained for 2-chloropyridine (**5q**) and *p*-chloronitrobenzene (**5r**), respectively (entries 24 and 25). While cross-coupling reaction of 3-chloropyridine (**5s**) and *p*-chloroacetophenone (**5t**) gave products in low yields (entries 26 and 27).

## 3. Conclusion

In summary, the cyclopalladated ferrocenylimine **1** or **2** in the presence of CuI is efficient catalyst for the homocoupling reactions of terminal alkynes to synthesize 1,3-diynes in the air. Several functional groups can be tolerated in this reaction. The cyclopalladated ferrocenylimine **2** as the catalyst with *n*-$Bu_4NBr$ can be applied to Sonogashira cross-coupling reaction of aryl halides with various terminal alkynes under amine- and copper-free conditions. The aryl halides can be extended to some activated aryl chlorides. Further studies on these two reactions are undergoing in our group.

## 4. Experimental

### 4.1. General methods

$^1H$ NMR and $^{13}C$ NMR spectra were recorded on a Bruker DPX-400 spectrometer with $CDCl_3$ as the solvent and TMS as an internal standard. Melting points were measured using a WC-1 microscopic apparatus and are uncorrected. GC analysis was performed on Agilent 4890D gas chromatograph. High-resolution mass spectra were measured on a Waters Q-Tof Micro™ spectrometer. Compound **3h** was synthesized according to the literature.[15] The other chemicals were reagent grade and used without further purification. All of the products **4** and **6** except **4h** were known and the purified products were identified by comparison of melting points, $^1H$ NMR or $^{13}C$ NMR spectra with the literatures.

### 4.2. Typical experimental procedure for the homocoupling of alkynes

A mixture of alkyne **3** (1 mmol), palladacycle, CuI (2.5 mol %), base, and solvent (2.5 mL) was stirred under air in preheated oil bath followed by TLC or GC. After the reaction was finished, 10 mL water was added. The mixture was extracted with ethyl acetate. The combined organic phases were washed with water, dried over anhydrous $Na_2SO_4$, and filtered. The solvent was removed on a rotary evaporator. The residue was purified by column chromatography using hexane or hexane/ethyl acetate as an eluent to afford pure **4**.

**4.2.1. 1,4-Diphenyl buta-1,3-diyne (4a).[6h]** White solid, mp 86–88 °C (lit. 88 °C); $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$: 7.54–7.52 (m, 4H), 7.38–7.34 (m, 6H); $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$: 132.5, 129.2, 128.5, 121.8, 81.5, 73.9.

**4.2.2. 1,4-Bis(*p*-pentylphenyl)buta-1,3-diyne (4b).**[16a] White solid, mp 85–86 °C (lit. 86 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.43 (d, $J$=8.00 Hz, 4H), 7.14 (d, $J$=8.00 Hz, 4H), 2.60 (t, $J$=7.80 Hz, 4H), 1.65–1.50 (m, 4H), 1.36–1.25 (m, 8H), 0.89 (t, $J$=6.80 Hz, 6H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 144.9, 132.8, 129.0, 119.4, 82.0, 73.9, 36.4, 31.8, 31.3, 22.9, 14.4.

**4.2.3. 1,4-Bis(3-pyridyl)buta-1,3-diyne (4c).**[16b] White solid, mp 144–146 °C (lit. 145–146 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.79 (s, 2H), 8.62 (d, $J$=4.00 Hz, 2H), 7.86 (d, $J$=8.00 Hz, 2H), 7.34 (t, $J$=4.80 Hz, 2H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 152.7, 149.0, 139.9, 123.3, 119.1, 79.1.

**4.2.4. Tetradeca-6,8-diyne (4d).**[6h] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 2.25 (t, $J$=7.20 Hz, 4H), 1.54–1.48 (m, 4H), 1.39–1.28 (m, 8H), 0.89 (t, $J$=7.20 Hz, 6H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 77.5, 65.1, 31.0, 28.0, 22.1, 19.1, 13.9.

**4.2.5. Eicosa-9,11-diyne (4e).**[6h] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 2.24 (t, $J$=7.50 Hz, 4H), 1.57–1.50 (m, 4H), 1.41–1.35 (m, 4H), 1.34–1.20 (m, 16H), 0.88 (t, $J$=6.60 Hz, 6H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 77.6, 65.2, 31.8, 29.2, 29.1, 28.9, 28.3, 22.7, 19.2, 14.1.

**4.2.6. 2,7-Dimethyl octa-3,5-diyne-2,7-diol (4f).**[12] White needles, mp 131 °C (lit. 131–133 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 1.89 (s, 2H), 1.54 (s, 12H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 84.0, 66.3, 65.6, 31.0.

**4.2.7. 1,4-Bis(1-hydroxycyclohexyl)buta-1,3-diyne (4g).**[6h] White solid, mp 175 °C (lit. 173–175 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 1.95–1.91 (m, 4H), 1.82 (s, 2H), 1.71 (t, $J$=8.00 Hz, 4H), 1.63–1.53 (m, 8H), 1.26–1.20 (m, 4H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 83.0, 69.2, 68.3, 39.7, 25.0, 23.1.

**4.2.8. Methacrylic acid-2,7-dimethyl octa-3,5-diyne-2,7-diyl ester (4h).** Yellow oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 6.06 (s, 2H, $CH_2$=), 5.55 (m, 2H, $CH_2$=), 1.92 (d, $J$=0.80 Hz, 6H, C=C–$CH_3$), 1.70 (s, 12H, $C(CH_3)_2$–C≡C); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 165.5, 136.7, 125.6, 80.3, 71.9, 68.5, 28.7, 18.2; IR (film): 3023, 2991, 2153, 1724, 1466, 1382, 1326, 1231, 1176, 1120, 1008, 939, 857, 811, 729; HRMS (positive ESI) calcd for $C_{18}H_{22}O_4$ $[M+Na]^+$: 325.1416, found: 325.1404.

### 4.3. Typical experimental procedure for Sonogashira reaction of ArX with terminal alkynes

Under nitrogen atmosphere, a mixture of ArX (0.5 mmol), alkyne (0.6 mmol), palladacycle **2**, $n$-$Bu_4NBr$ (0.75 mmol), KOAc (0.75 mmol), and DMA (2.5 mL) was stirred at 80 or 110 °C in an oil bath followed by TLC or GC. After the reaction was finished, 10 mL water was added, and the mixture was extracted with ethyl acetate. The combined organic phases were washed with water, dried over anhydrous $Na_2SO_4$, and filtered. The solvent was removed under reduced pressure. The residue was purified by column chromatography using hexane or hexane/ethyl acetate as an eluent to afford pure **6**.

**4.3.1. Diphenylacetylene (6aa).**[9d] White solid, mp 58–61 °C (lit. 60–62 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.62–7.52 (m, 4H), 7.42–7.28 (m, 6H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 132.0, 128.7, 128.6, 123.7, 89.7.

**4.3.2. (*p*-Tolyl)phenylacetylene (6ba).**[17] White solid, mp 71–72 °C (lit. 72–73 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.54–7.49 (d, $J$=8.08 Hz, 2H), 7.42 (d, $J$=8.08 Hz, 2H), 7.34–7.32 (m, 3H), 7.14 (d, $J$=8.00 Hz, 2H), 2.36 (s, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 138.4, 131.6, 131.5, 129.1, 128.3, 128.0, 123.5, 120.2, 89.6, 88.7, 21.5.

**4.3.3. (3-Tolylphenyl)acetylene (6ca).**[18] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.55–7.50 (m, 2H), 7.40–7.29 (m, 5H), 7.27–7.10 (m, 2H), 2.36 (s, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 138.0, 132.2, 131.6, 129.2, 128.7, 128.3, 128.2, 128.1, 123.3, 123.0, 89.5, 89.0, 21.3.

**4.3.4. (3-Methoxyphenyl)phenylacetylene (6da).**[18] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.56–7.49 (m, 2H), 7.42–7.30 (m, 3H), 7.30–7.21 (m, 1H), 7.18–7.10 (m, 1H), 7.08–7.01 (m, 1H), 6.95–6.85 (m, 1H), 3.83 (s, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 159.3, 131.6, 129.4, 128.4, 128.3, 124.2, 124.1, 123.1, 116.2, 115.0, 89.3, 89.2, 55.3.

**4.3.5. (*p*-Methoxyphenyl)phenylacetylene (6ea).**[9d] White solid, mp 59–60 °C (lit. 57–61 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.53–7.50 (m, 2H), 7.50–7.45 (m, 2H), 7.37–7.30 (m, 3H), 6.89–6.86 (d, $J$=8.80 Hz, 2H), 3.83 (s, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 159.6, 133.1, 131.5, 128.3, 128.0, 123.6, 115.4, 114.0, 89.4, 88.1, 55.3.

**4.3.6. 1-Hexyl-4-[(4-methoxyphenyl)ethynyl]benzene (6eb).**[19] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.50–7.35 (m, 4H), 7.13 (d, $J$=8.00 Hz, 2H), 6.90–6.80 (m, 2H), 2.60 (t, $J$=7.90 Hz, 2H), 1.63–1.58 (m, 2H), 1.35–1.25 (m, 4H), 0.89 (t, $J$=6.50 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 159.5, 143.1, 133.0, 131.3, 128.4, 120.7, 115.6, 114.0, 88.7, 88.2, 55.3, 35.9, 31.4, 30.9, 22.5, 14.0.

**4.3.7. 1-(Hept-1-ynyl)-4-methoxy benzene (6ed).**[20] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.32 (d, $J$=7.40 Hz, 2H), 6.81 (d, $J$=7.40 Hz, 2H), 3.81 (s, 3H), 2.38 (t, $J$=7.11 Hz, 2H), 1.62–1.55 (m, 2H), 1.45–1.25 (m, 4H), 0.92 (t, $J$=7.20 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 159.0, 132.9, 116.3, 113.8, 88.8, 80.2, 55.2, 31.2, 28.6, 22.3, 19.4, 14.0.

**4.3.8. 1-(Dec-1-ynyl)-4-methoxy benzene (6ee).**[9d] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.32 (d, $J$=8.80 Hz, 2H), 6.80 (d, $J$=8.80 Hz, 2H), 3.80 (s, 3H), 2.38 (t, $J$=7.50 Hz, 3H), 1.61–1.55 (m, 2H), 1.46–1.41 (m, 2H), 1.40–1.25 (m, 12H), 0.88 (t, $J$=6.80 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 159.0, 132.8, 116.3, 113.8, 88.8, 80.2, 55.2, 31.8, 29.2, 29.1, 28.9, 28.8, 22.7, 19.4, 14.1.

**4.3.9. 4-(4-Methoxyphenyl)-2-methyl-3-butyn-2-ol (6ef).**[20] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.34 (d, $J$=8.80 Hz, 2H), 6.82 (d, $J$=8.80 Hz, 2H), 3.80 (s, 3H), 2.08 (s, 1H), 1.61 (s, 6H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 159.5, 133.0, 114.8, 113.9, 92.4, 82.0, 65.6, 55.3, 31.6.

**4.3.10. 1-Nitro-4-(phenylethynyl)benzene (6fa).**[9d] Yellow solid, mp 119–120 °C (lit. 118–120 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.22 (d, $J$=8.80 Hz, 2H), 7.66 (d, $J$=8.80 Hz, 2H), 7.60–7.54 (m, 2H), 7.41–7.38 (m, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 147.0, 132.3, 131.9, 130.3, 129.3, 128.6, 123.7, 122.1, 94.7, 87.6.

**4.3.11. 1-Hexyl-4-[(4-nitrophenyl)ethynyl]benzene (6fb).**[21] Yellow solid, mp 66–68 °C (lit. 70–71 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.21 (d, $J$=8.80 Hz, 2H), 7.65 (d, $J$=8.80 Hz, 2H), 7.47 (d, $J$=8.00 Hz, 2H), 7.20 (d, $J$=8.00 Hz, 2H), 2.63 (t, $J$=7.80 Hz, 2H), 1.65–1.55 (m, 2H), 1.36–1.29 (m, 4H), 0.89 (t, $J$=7.20 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 146.8, 144.7, 132.2, 131.8, 130.6, 128.7, 123.7, 119.2, 95.2, 87.1, 36.0, 31.4, 30.9, 22.5, 14.0.

**4.3.12. 1-(Dec-1-ynyl)-4-nitrobenzene (6fe).**[9d] Colorless oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.15 (d, $J$=8.80 Hz, 2H), 7.51 (d, $J$=8.80 Hz, 2H), 2.44 (t, $J$=7.20 Hz, 2H), 1.66–1.58 (m, 2H), 1.49–1.41 (m, 2H), 1.32–1.25 (m, 8H), 0.89 (t, $J$=7.20 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 146.6, 132.2, 131.3, 123.5, 96.9, 79.3, 31.9, 29.2, 29.1, 29.0, 28.4, 22.7, 19.6, 14.1.

**4.3.13. (4-Cyanophenyl)phenylacetylene (6ga).**[22] White solid, mp 107–109 °C (lit. 108.5–109.5 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.65–7.60 (m, 4H), 7.59–7.53 (m, 2H), 7.40–7.35 (m, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 132.1, 132.1, 131.8, 129.1, 128.5, 128.3, 122.2, 118.5, 111.5, 93.8, 87.7.

**4.3.14. (4-Acetylphenyl)phenylacetylene (6ha).**[23] White solid, mp 95–96 °C (lit. 94–96 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.94 (d, $J$=8.41 Hz, 2H), 7.61 (d, $J$=8.41 Hz, 2H), 7.57–7.55 (m, 2H), 7.38–7.36 (m, 3H), 2.62 (s, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 197.3, 136.2, 131.8, 131.7, 128.9, 128.5, 128.3, 128.2, 122.7, 92.7, 88.6, 26.6.

**4.3.15. (2-Phenylethynyl)pyridine (6ia).**[24] Yellow oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.63 (d, $J$=4.48 Hz, 1H), 7.70 (td, $J$=7.91, 1.44 Hz, 1H), 7.65–7.58 (m, 2H), 7.54 (d, $J$=7.80 Hz, 1H), 7.41–7.33 (m, 3H), 7.26–7.20 (m, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 150.0, 143.4, 136.3, 132.1, 129.0, 128.4, 127.2, 122.8, 122.2, 89.4, 88.5.

**4.3.16. (3-Phenylethynyl)pyridine (6ja).**[20] Yellow solid, mp 48–49 °C (lit. 50–51 °C); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.78 (s, 1H), 8.56 (s, 1H), 7.83 (d, $J$=7.88 Hz, 1H), 7.60–7.49 (m, 2H), 7.45–7.35 (m, 3H), 7.35–7.27 (m, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 152.0, 148.3, 138.7, 131.7, 128.9, 128.5, 123.2, 122.5, 120.7, 92.9, 85.8.

**4.3.17. (2-Phenylethynyl)thiophene (6ka).**[25] Yellow oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.60–7.48 (m, 2H), 7.40–7.30 (m, 3H), 7.30–6.90 (m, 2H), 7.02 (d, $J$=4.00 Hz, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 131.9, 131.4, 128.4, 128.4, 127.2, 127.1, 123.3, 123.0, 93.0, 82.6.

**4.3.18. (3-Phenylethynyl)thiophene (6la).**[26] Yellow oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.58–7.46 (m, 3H), 7.39–7.31 (m, 3H), 7.31–7.27 (m, 1H), 7.22–7.15 (m, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 131.5, 129.9, 128.6, 128.4, 128.2, 125.4, 123.2, 122.3, 88.8, 84.5.

**4.3.19. (*p*-Chlorophenyl)phenylacetylene (6ma).**[27] Yellow oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 7.56–7.48 (m, 2H), 7.48–7.42 (m, 2H), 7.37–7.32 (m, 4H), 7.32–7.29 (m, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 134.7, 133.2, 132.0, 129.1, 128.9, 128.8, 123.3, 122.2, 90.7, 88.6.

**4.3.20. (1-Phenylethynyl)naphthalene (6na).**[28] Yellow oil; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$: 8.47–8.42 (m, 1H), 7.90–7.59 (m, 3H), 7.68–7.26 (m, 8H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$: 133.4, 133.3, 131.8, 130.5, 128.9, 128.6, 128.5, 128.4, 126.8, 126.5, 126.3, 125.4, 123.5, 121.0, 94.5, 87.7.

## Acknowledgements

We are grateful to the National Natural Science Foundation of China (No. 20472074) and the Innovation Fund for Outstanding Scholar of Henan Province (No. 0621001100) for the financial support of this research.

## References and notes

1. Bohlmann, F.; Burkhart, F. T.; Zero, C. *Naturally Occurring Acetylenes*; Academic: London and New York, NY, 1973.
2. Hunstman, V. D. *The Chemistry of the Carbon–Carbon Triple Bond*; Patai, S., Ed.; Wiley-Interscience: London, 1978; pp 553–620.
3. (a) Paterson, I.; Davies, R. D.; Marquez, R. *Angew. Chem., Int. Ed.* **2001**, *40*, 603; (b) Sonogashira, K. *J. Organomet. Chem.* **2002**, *653*, 46; (c) Negishi, E.; Anastasia, L. *Chem. Rev.* **2003**, *103*, 1979; (d) Nicolaou, K. C.; Bulger, P. G.; Sarlah, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4442.
4. For representative reviews on palladium-catalyzed homocoupling reactions of alkynes, see: (a) Siemsen, P.; Livingston, R. C.; Diederich, F. *Angew. Chem., Int. Ed.* **2000**, *39*, 2632; (b) Negishi, E.; Alimardanov, A. *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E., Ed.; Wiley-Interscience: New York, NY, 2002; Vol. 1, p 989.
5. For representative reviews on palladium-catalyzed Sonogashira reactions of alkynes, see: (a) Sonogashira, K. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: New York, NY, 1991; Vol. 3, pp 521–549; (b) Rossi, R.; Carpita, A.; Bellina, F. *Org. Prep. Proced. Int.* **1995**, *27*, 129; (c) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, UK, 1995; pp 168–171; (d) Nicolaou, K. C.; Sorensen, E. J. *Classics in Total Synthesis*; VCH: Weinheim, Germany, 1996; pp 582–586; (e) Brandsma, L.; Vasilevsky, S. F.; Verkruijsse, H. D. *Application of Transition Metal Catalysts in Organic Synthesis*; Springer: Berlin, 1998; pp 179–225; (f) Sonogashira, K. *Metal-Catalyzed Cross-Coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: Weinheim, Germany, 1998; pp 203–229.
6. For palladium-catalyzed homocoupling of alkynes, see: (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, *16*, 4467; (b) Vlassa, M.; Ciocan-Tarta, I.; Margineanu, F.; Oprean, I. *Tetrahedron* **1996**, *52*, 1337; (c) Li, J.; Mau, A. W.-H.; Strauss, C. R. *Chem. Commun.* **1997**, 1275; (d) Li, J.; Jiang, H. *Chem. Commun.* **1999**, 2369; (e) Chao, D. H.; Lee, J. H.; Kim, B. H. *J. Org. Chem.* **1999**, *66*, 8480; (f) Lei, A.;

Srivastava, M.; Zhang, X. *J. Org. Chem.* **2002**, *67*, 1969; (g) Li, J.-H.; Liang, Y.; Xie, Y.-X. *J. Org. Chem.* **2005**, *70*, 4393; (h) Li, J.-H.; Liang, Y.; Zhang, X.-D. *Tetrahedron* **2005**, *61*, 1903; (i) Shi, M.; Qian, H.-X. *Appl. Organomet. Chem.* **2006**, *20*, 771.

7. Batsanov, A. S.; Collings, J. C.; Fairlamb, I. J. S.; Holland, J. P.; Howard, J. A. K.; Lin, Z.-Y.; Marder, T. B.; Parsons, A. C.; Ward, R. M.; Zhu, J. *J. Org. Chem.* **2005**, *70*, 703.
8. For selected papers on the palladium/phosphine/CuI/amine system for the Sonogashira cross-coupling reactions, see: (a) Hundertmark, T.; Litter, A. F.; Buchwald, S. L.; Fu, G. C. *Org. Lett.* **2000**, *2*, 1729; (b) Chow, H.-F.; Wan, C.-W.; Low, K.-H.; Yeung, Y.-Y. *J. Org. Chem.* **2001**, *66*, 1910; (c) Novák, Z.; Szabó, A.; Répási, J.; Kotschy, A. *J. Org. Chem.* **2003**, *68*, 3327; (d) Hierso, J.-C.; Fihri, A.; Amardeil, R.; Meunier, P. *Org. Lett.* **2004**, *6*, 3473; (e) Son, S. U.; Jang, Y.; Park, J.; Na, H. B.; Park, H. M.; Yun, H. J.; Lee, J.; Hyeon, T. *J. Am. Chem. Soc.* **2004**, *126*, 5026; (f) Adjabeng, G.; Brenstrum, T.; Frampton, C. S.; Robertson, A. J.; Hillhous, J.; McNulty, J.; Capretta, A. *J. Org. Chem.* **2004**, *69*, 5082; (g) Shao, L.-X.; Shi, M. *J. Org. Chem.* **2005**, *70*, 8635.
9. For recent papers on palladium-catalyzed Sonogashira reaction under copper free conditions, see: (a) Leadbeater, N. E.; Tominack, B. J. *Tetrahedron Lett.* **2003**, *44*, 8653; (b) Liang, B.; Dai, M.; Chen, J.-H.; Yang, Z. *J. Org. Chem.* **2005**, *70*, 391; (c) Gholap, A. R.; Venkatesan, K.; Pasricha, R.; Daniel, T.; Lahoti, R. J.; Srinivasan, K. V. *J. Org. Chem.* **2005**, *70*, 4869; (d) Li, P.-H.; Wang, L.; Li, H.-J. *Tetrahedron* **2005**, *61*, 8633; (e) Shirakawa, E.; Kitabata, T.; Otsuka, H.; Tsuchimoto, T. *Tetrahedron* **2005**, *61*, 9878; (f) Liang, Y.; Xie, Y.-X.; Li, J.-H. *J. Org. Chem.* **2006**, *71*, 379; (g) Yi, C.-Y.; Hua, R.-M. *J. Org. Chem.* **2006**, *71*, 2535.
10. (a) Glaser, C. *Ber. Dtsch. Chem. Ges.* **1869**, *2*, 422; (b) Hay, A. S. *J. Org. Chem.* **1962**, *27*, 3320; (c) Rossi, R.; Carpita, A.; Begelli, C. *Tetrahedron Lett.* **1985**, *26*, 523; (d) Liu, Q.; Burton, D. J. *Tetrahedron Lett.* **1997**, *38*, 371.
11. For representative reviews, see: (a) Bedford, R. B. *Chem. Commun.* **2003**, 1787; (b) Herrmann, W. A.; Ofele, K.; Preysing, D. V. *J. Organomet. Chem.* **2003**, *687*, 229; (c) Bedford, R. B.; Cazin, C. S. J.; Holder, D. *Coord. Chem. Rev.* **2004**, *248*, 2283; (d) Beletskaya, J. P.; Cheprakov, A. V. *J. Organomet. Chem.* **2004**, *689*, 4055.
12. Alonso, D. A.; Nájera, C.; Pacheco, M. C. *Adv. Synth. Catal.* **2003**, *345*, 1146.
13. Consorti, C. S.; Flore, F. R.; Rominger, F.; Dupont, J. *Adv. Synth. Catal.* **2006**, *348*, 133.
14. For the preparation of the cyclopalladated ferrocenylimines, see: Huo, S.-Q.; Wu, Y.-J.; Du, C.-X.; Zhu, Y.; Yuan, H.-Z.; Mao, X.-A. *J. Organomet. Chem.* **1994**, *483*, 139.
15. Yadav, V. K.; Babu, K. G. *J. Org. Chem.* **2004**, *69*, 577.
16. (a) Wu, S.-T.; Finkenzeller, U.; Reiffenrath, V. *J. Appl. Phys.* **1989**, *65*, 4372; (b) Rodríguez, J. G.; Martín-Villamil, R.; Cano, F. H.; Fonseca, I. *J. Chem. Soc., Perkin Trans. 1* **1997**, 709.
17. Paquett, L. A.; Wittenbrook, L. S. *J. Am. Chem. Soc.* **1967**, *89*, 4483.
18. Alagille, D.; Baldwin, R. M.; Roth, B. L.; Wroblewski, J. T.; Grajkowska, E.; Tamagnan, G. D. *Bioorg. Med. Chem.* **2005**, *13*, 197.
19. Jacques, J. *Ger. Offen.* **1972**, 18.
20. Cheng, J.; Sun, Y.-H.; Wang, F.; Guo, M.-J.; Xu, J.-H.; Pan, L.; Zhang, Z.-G. *J. Org. Chem.* **2004**, *69*, 5428.
21. Spadlo, A.; Dabrowski, R.; Filipowicz, M.; Stolarz, Z.; Przedmojski, J.; Gauza, S.; Fan, C. Y. H.; Wu, S.-T. *Liq. Cryst.* **2003**, *30*, 191.
22. Yoshida, K.; Fueno, T. *J. Org. Chem.* **2003**, *38*, 1045.
23. Arcadi, A.; Cacchi, S.; Fabrizi, G.; Marinelli, F.; Pace, P. *Eur. J. Org. Chem.* **1999**, *12*, 3305.
24. Agawa, T.; Miller, S. I. *J. Am. Chem. Soc.* **1961**, *83*, 449.
25. Mori, Y.; Seki, M. *J. Org. Chem.* **2003**, *68*, 1517.
26. Van den Hoven, B. G.; Alper, H. *J. Org. Chem.* **1999**, *64*, 9640.
27. Gil-Moltó, J.; Karlström, S.; Nájera, C. *Tetrahedron* **2005**, *61*, 12168.
28. Katritzky, A. R.; Abdel-Fattah, A. A. A.; Wang, M.-Y. *J. Org. Chem.* **2002**, *67*, 7526.