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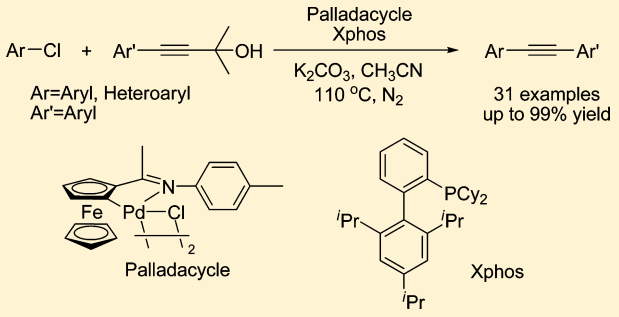
Palladacycle-Catalyzed Deacetonative Sonogashira Coupling of Aryl Propargyl Alcohols with Aryl Chlorides

Hao Hu, Fan Yang,* and Yangjie Wu*

The College of Chemistry and Molecular Engineering, Henan Key Laboratory of Chemical Biology and Organic Chemistry, Key Laboratory of Applied Chemistry of Henan Universities, Zhengzhou University, Zhengzhou 450052, People's Republic of China

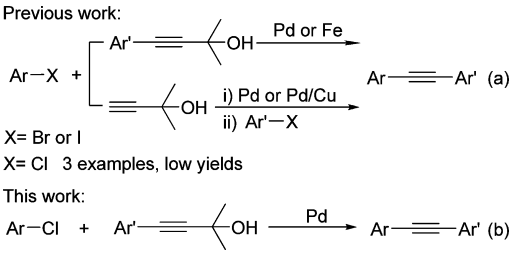
Supporting Information

ABSTRACT: An efficient and general protocol for the deacetonative Sonogashira coupling of aryl propargyl alcohols with aryl chlorides is described. The reaction proceeded smoothly with the catalyst system of palladacycle/Xphos. This result represents the first successful deacetonative Sonogashira version for electron-poor, electron-neutral, and even inactive sterically hindered electron-rich aryl chlorides.



The Sonogashira reaction has been one of the most straightforward and efficient tools for C(sp)−C(sp^2) bond-forming reactions, thereby dominating the synthesis of diaryl acetylenes.[1] Significant progress has been achieved in the coupling of commercially available aryl chlorides by Buchwald, Fu, and others.[2] However, this reaction still suffers from some limitations, especially the problem of poor tolerance to electron-poor terminal alkynes and generation of diynes as byproducts.[3] To address these challenges, decarboxylative and deacetonative Sonogashira couplings have emerged as two promising alternatives within recent years.[4,5] In particular, deacetonative coupling was first reported in 2001 by Chow's group, who described a $PdCl_2(PPh_3)_2$/CuI-catalyzed tandem catalytic reaction of aryl-2-methyl-3-butyn-2-ol with aryl bromides (Scheme 1a).[5a] Subsequently, significant progress has been achieved by the groups of Kotschy, Shirakawa, Hua, and Tsai (Scheme 1a).[5b−f] Especially, Hua and co-workers developed the first deacetonative Sonogashira reaction of aryl chlorides using $PdCl_2(PCy_3)_2$ as the catalyst. This protocol is quite effective for the synthesis of symmetrical diaryl acetylenes but provided only three examples for unsymmetrical diaryl acetylenes with low yields.[5d] Recently, Tsai and co-workers described $FeCl_3$-catalyzed one-pot Sonogashira−Hagihara coupling of aryl iodides with aryl propargyl alcohols.[5f] However, the substrate scope in the above-mentioned reports is mainly limited to aryl iodides and bromides, and successful examples for commercially available aryl chlorides remain rare. From the viewpoint of synthetic cost, developing a generally applicable catalytic system for aryl chlorides would be challenging but highly desirable (Scheme 1b).

Scheme 1. Synthesis of Unsymmetrical Diaryl Acetylenes via Catalytic Deacetonative Sonogashira Coupling



In recent years, our research group has focused on the catalytic application of a family of versatile palladacyclic catalysts: cyclopalladated ferrocenylimines (Figure 1).[6] The bulky alkylphosphine ligands were developed in Buchwald's group and have been widely applied to the cross-coupling of aryl chlorides.[2d] Just recently, with the aid of the palladacycle and an alkylphosphine ligand, we realized the first successful decarboxylative Sonogashira reaction of alkynyl carboxylic acids with aryl chlorides in xylene/H_2O.[6g] To further explore another alternative catalytic version of the traditional Sonogashira reaction, in this work we attempted to fulfill the palladacycle/alkylphosphine-catalyzed deacetonative Sonogashira reaction of aryl propargyl alcohol with aryl chlorides to facilitate the industrial demand.

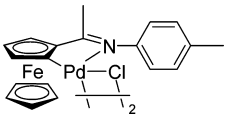


Figure 1. Palladacycle: cyclopalladated ferrocenylimine.

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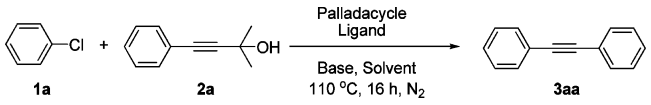
We began the reaction conditions optimization with the reaction of chlorobenzene (**1a**) and 4-phenyl-2-methyl-3-butyne-2-ol (**2a**) in DMF using Xphos as the ligand, and a relatively low but promising isolated yield of 48% was observed (Table 1, entry 1). Next, other solvents (e.g., DMA, DMSO, dioxane, toluene, and CH_3CN) were evaluated, and to our surprise, CH_3CN gave up to 96% yield (Table 1, entries 1−6). Some other bases (e.g., KOH, KF, KOAc, NaOH, and Na_2CO_3) were also employed, and only K_3PO_4 could lead to a moderate yield of 76% (Table 1, entries 7−12). Subsequently, different ligands such as PPh_3, 2-dicyclohexylphosphino-2′-(*N*,*N*-dimethylamino)biphenyl (Davephos), and 1,1′-bis-(diphenylphosphino)ferrocene (dppf) were also screened, and unfortunately, no products were observed (Table 1, entries 13−15). Performing reaction under air in place of nitrogen or at a lower oil bath temperature of 90 °C resulted in lower yields (Table 1, entries 16 and 17), which indicated that both the nitrogen atmosphere and the temperature play key roles in this reaction. Finally, some commercially available transition-metal sources such as $PdCl_2$, $Pd(OAc)_2$, $Pd_2(dba)_3$, $NiCl_2$, and CuI were also checked and did not display better catalytic activity (Table 1, entries 18−22).

Table 1. Screening for Optimal Conditions[a]



1a **2a** **3aa**

entry	ligand	solvent	base	yield (%)
1	Xphos	DMF	K_2CO_3	48
2	Xphos	DMA	K_2CO_3	67
3	Xphos	DMSO	K_2CO_3	60
4	Xphos	dioxane	K_2CO_3	46
5	Xphos	toluene	K_2CO_3	39
6	**Xphos**	**CH_3CN**	**K_2CO_3**	**96**
7	Xphos	CH_3CN	K_3PO_4	76
8	Xphos	CH_3CN	KOH	<5
9	Xphos	CH_3CN	KF	<5
10	Xphos	CH_3CN	KOAc	<5
11	Xphos	CH_3CN	NaOH	<5
12	Xphos	CH_3CN	Na_2CO_3	<5
13	PPh_3	CH_3CN	K_2CO_3	<5
14	Davephos	CH_3CN	K_2CO_3	<5
15	Dppf	CH_3CN	K_2CO_3	<5
16[b]	Xphos	CH_3CN	K_2CO_3	25
17[c]	Xphos	CH_3CN	K_2CO_3	20
18[d]	Xphos	CH_3CN	K_2CO_3	32
19[e]	Xphos	CH_3CN	K_2CO_3	<5
20[f]	Xphos	CH_3CN	K_2CO_3	28
21[g]	Xphos	CH_3CN	K_2CO_3	<5
22[h]	Xphos	CH_3CN	K_2CO_3	<5

[a]Reaction conditions: **1a** (0.4 mmol), **2a** (0.5 mmol), palladacycle (1 mol %), ligand (4 mol %), and base (1.0 mmol) in solvent (2.0 mL) at 110 °C (oil bath temperature) under a nitrogen atmosphere for 16 h. [b]Under air. [c]At 90 °C (oil bath temperature). [d]$PdCl_2$ (2 mol %) was used instead of the palladacycle. [e]$Pd(OAc)_2$ (2 mol %) was used instead of the palladacycle. [f]$Pd_2(dba)_3$ (1 mol %) was used instead of the palladacycle. [g]$NiCl_2$ (5 mol %)/Xphos (10 mol %) was used instead of the palladacycle. [h]CuI (5 mol %)/Xphos (10 mol %) was used instead of the palladacycle.

With the optimized reaction conditions in hand, we then examined the substrate scope of aryl chlorides (Table 2). Generally, electronic and *ortho*-steric effects had no significant influence on this coupling, and the reactions could tolerate various functional groups such as MeO, NO_2, MeOOC, CN, and CF_3, leading to the desired products in good to excellent yields. Aryl chlorides bearing one *ortho*-sterically hindered group could be coupled with 4-phenyl-2-methyl-3-butyne-2-ol, leading to excellent isolated yields (Table 2, **3ea**, **3fa**, **3ia**, and **3oa**). Notably, even the more sterically hindered 2-chloro-*m*-xylene gave a 99% isolated yield (Table 2, **3ga**). Moreover, the reactions of some heteroaryl chlorides also smoothly generated the desired products in excellent yields (Table 2, **3sa**, **3ta**, **3ua**, and **3va**).

Subsequently, experiments were directed at establishing the scope of aryl propargyl alcohols (Table 3). The results indicated that electronic and steric effects have no obvious influence. Notably, sterically hindered aryl propargyl alcohols possessing one or two *ortho*-sterically hindered groups could be efficiently converted into the corresponding products in moderate yields of 76%, 42%, and 58% (Table 3, **3hd**, **3he**, and **3hi**, respectively). In addition, electron-withdrawing groups on the aryl ring did not hamper the coupling significantly, and the corresponding products were also obtained in yields of 78% and 75% (Table 3, **3hh** and **3hj**, respectively).

To indicate the advantage of the deacetonative coupling reaction over the traditional Sonogashira coupling, competitive reactions of 4-chloroanisole (**1h**) with 2-methyl-4-(4-nitrophenyl)-3-butyn-2-ol (**2j**) and 1-ethynyl-4-nitrobenzene (**4a**) were finally performed (Scheme 2). The reaction of **2j** generated the product **3hj** in a yield of 75%, while the coupling reaction of **4a** did not occur at all. These results indicate that the deacetonative coupling reaction can tolerate electron-poor alkynes well.

Our previous reports have indicated that the palladacycle just behaves as a reservoir of catalytically active Pd(0) species.[6d,g] On the basis of these related reports, a possible mechanism is outlined in Scheme 3. Initially, a Pd(0) species is released from the palladacycle to form the catalytically active species $Pd(0)L_2$ (**I**) with the alkylphosphine ligand. Next, oxidative addition of the aryl chloride (**1**) to $Pd(0)L_2$ takes place to afford Pd(II) intermediate **II**. Subsequently, the reaction of intermediate **II** with the aryl propargyl alcohol occurrs, forming the Pd(II) intermediate **III** via a deacetonative step in the presence of K_2CO_3. Finally, the desired product **3** and active catalyst $Pd(0)L_2$(**I**) are generated through reductive elimination of intermediate **III** to fulfill the catalytic cycle.

We have developed a general and efficient method for the deacetonative Sonogashira coupling of aryl propargyl alcohols with aryl chlorides using palladacycle/Xphos as the catalyst system, affording symmetrical and unsymmetrical diaryl acetylenes in mostly good to excellent yields. Notably, this deacetonative coupling is applicable to electron-poor, electron-neutral, and even inactive sterically hindered electron-rich aryl chlorides. Moreover, the reaction well tolerates electron-poor alkynes, for which the traditional Sonogashira reaction does not work.

EXPERIMENTAL SECTION

General Methods. ^1H and ^{13}C NMR spectra were recorded with $CDCl_3$ as the solvent and TMS as an internal standard. The palladacyclic catalyst was prepared according to the reported literature procedure.[6a] The other chemicals were bought from commercial sources and used as received, unless otherwise noted.

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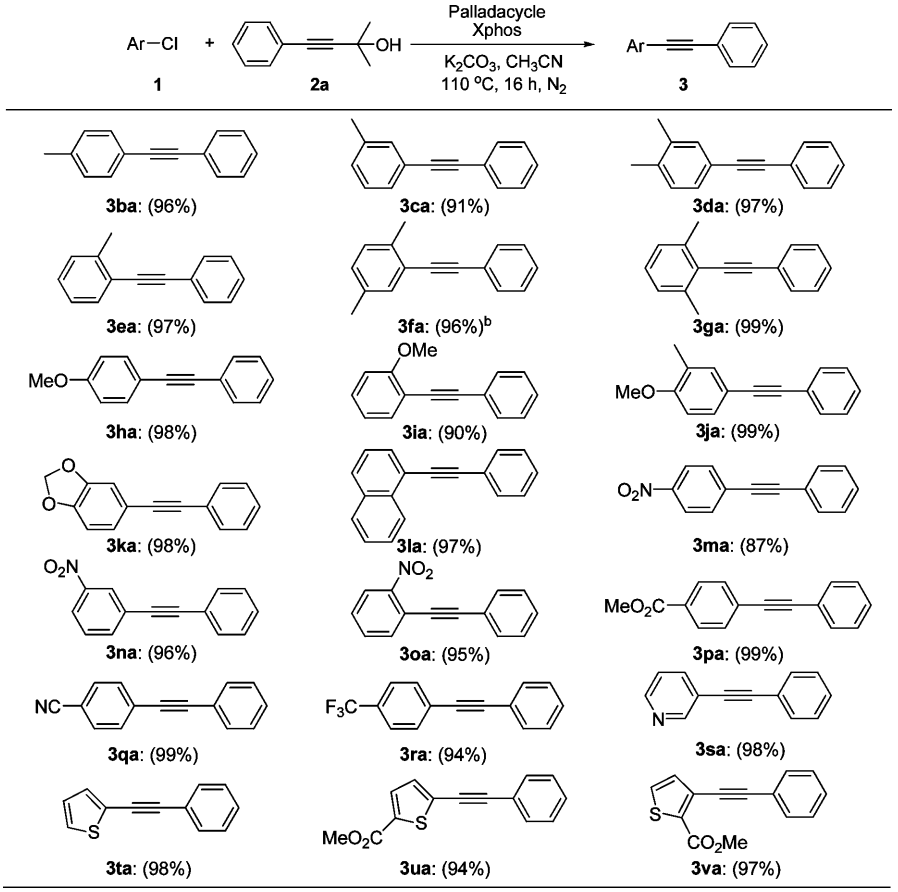
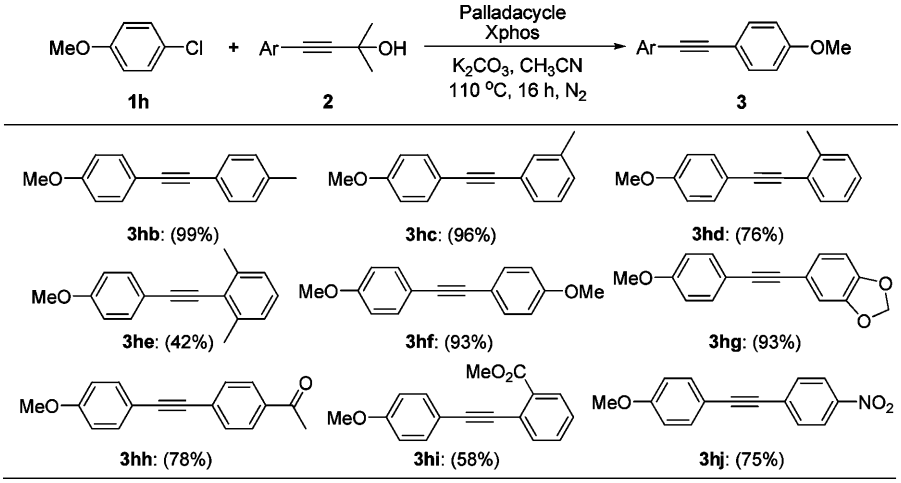
Table 2. Deacetonative Sonogashira Coupling of 4-Phenyl-2-methyl-3-butyne-2-ol with Aryl Chlorides[a]



[a]Reaction conditions: aryl chloride (0.4 mmol), 4-phenyl-2-methyl-3-butyne-2-ol (0.5 mmol), palladacycle (1 mol %), Xphos (4 mol %), and K_2CO_3 (1.0 mmol) in CH_3CN (2.0 mL) at 110 °C (oil bath temperature) under a nitrogen atmosphere for 16 h. [b]For 34 h.

Table 3. Deacetonative Sonogashira Coupling of Aryl Propargyl Alcohols with 4-Chloroanisole[a]



[a]Reaction conditions: 4-chloroanisole (0.4 mmol), 4-aryl-2-methyl-3-butyne-2-ol (0.5 mmol), palladacycle (1 mol %), Xphos (4 mol %), and K_2CO_3 (1.0 mmol) in CH_3CN (2.0 mL) at 110 °C (oil base temperature) under a nitrogen atmoshphere for 16 h.

Typical Procedure for the Palladacycle-Catalyzed Deacetonative Sonogashira Coupling of 4-Aryl-2-methyl-3-butyne-2-ols with Aryl Chlorides. Aryl chloride (0.4 mmol), 4-aryl-2-methyl-3-butyne-2-ol (0.5 mmol), K_2CO_3 (1.0 mmol), palladacycle (1 mol %), and Xphos (4 mol %) were dissolved in CH_3CN (2 mL) in a 10 mL vial under a nitrogen atmosphere. The reaction was carried out at 110 °C (oil bath temperature) for 16 h. After the reaction was finished, the mixture was filtered through a pad of Celite and extracted with brine and ethyl acetate three times. The combined organic layers were dried over anhydrous Na_2SO_4 and filtered. After removal of the solvent in vacuum, the residue was purified by flash column chromatography on silica gel (hexane/ethyl acetate) to afford the pure product.

*1,2-Diphenylethyne (**3aa**).*[7] White solid (68 mg, 96%), mp 61−62 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29−7.37 (m, 6H), 7.50−7.56 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 88.4, 122.2, 127.3, 127.3, 130.6.

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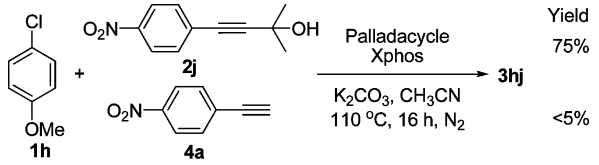
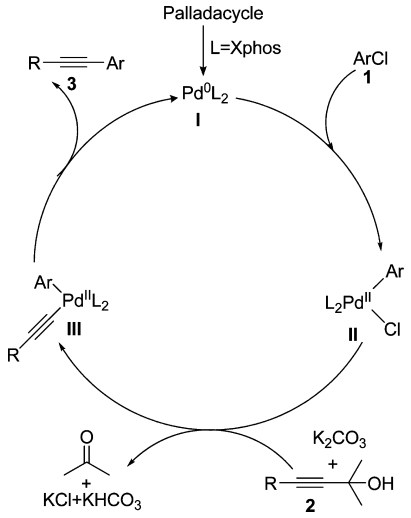
Scheme 2. Deacetonative Sonogashira Coupling versus Sonogashira Coupling



Scheme 3. Proposed Mechanism of Palladacycle-Catalyzed Deacetonative Sonogashira Reaction



1-Methyl-4-(phenylethynyl)benzene (**3ba**).[7] White solid (74 mg, 96%), mp 69−71 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.36 (s, 3H), 7.15 (d, J = 7.6 Hz, 2H), 7.28−7.37 (m, 3H), 7.42 (d, J = 7.2 Hz, 2H), 7.48−7.55 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.3, 88.5, 89.3, 119.9, 123.2, 127.8, 128.1, 128.9, 131.3, 131.3, 138.1.

3-Phenylethynyltoluene (**3ca**).[4c] Colorless oil (70 mg, 91%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.34 (s, 3H), 7.13 (d, J = 7.6 Hz, 1H), 7.23 (t, J = 7.6 Hz, 1H), 7.29−7.39 (m, 5H), 7.49−7.55 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.2, 88.0, 88.5, 122.0, 122.3, 127.2, 127.2, 127.3, 127.7, 128.2, 130.6, 131.2, 137.0.

1,2-Dimethyl-4-(phenylethynyl)benzene (**3da**).[6g] White solid (80 mg, 97%), mp 61−62 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.25 (s, 3H), 2.26 (s, 3H), 7.10 (d, J = 7.7 Hz, 1H), 7.27 (d, J = 7.2 Hz, 1H), 7.30−7.36 (m, 4H), 7.49−7.54 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 18.6, 18.8, 87.5, 88.7, 119.5, 122.6, 127.0, 127.3, 128.1, 128.7, 130.5, 131.6, 135.7, 136.2.

1-Methyl-2-(phenylethynyl)benzene (**3ea**).[6g] Colorless oil (75 mg, 97%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.54 (s, 3H), 7.14−7.21 (m, 1H), 7.23−7.24 (m, 2H), 7.31−7.38 (m, 3H), 7.49−7.59 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.0, 88.6, 93.6, 123.2, 123.8, 125.8, 128.4, 128.5, 128.6, 129.7, 131.7, 132.0, 140.4.

1,4-Dimethyl-2-(phenylethynyl)benzene (**3fa**).[6g] Light-yellow solid (79 mg, 96%), mp 77−79 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.31 (s, 3H), 2.47 (s, 3H), 7.04 (d, J = 7.7 Hz, 1H), 7.11 (d, J = 7.8 Hz, 1H), 7.30−7.37 (m, 4H), 7.50−7.55 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.2, 20.8, 88.6, 93.0, 122.8, 123.7, 128.1, 128.4, 129.2, 129.4, 131.5, 132.3, 135.1, 137.1.

1,3-Dimethyl-2-(phenylethynyl)benzene (**3ga**).[6g] Colorless oil (82 mg, 99%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.50 (s, 6H), 7.02−7.14 (m, 3H), 7.29−7.36 (m, 3H), 7.51−7.55 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.9, 87.0, 97.7, 122.8, 123.7, 126.5, 127.6, 127.9, 128.2, 131.2, 140.1.

1-Methoxy-4-(phenylethynyl)benzene (**3ha**).[8] Light-yellow solid (82 mg, 98%), mp 55−56 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.82 (s, 3H), 6.85−6.90 (m, 2H), 7.29−7.36 (m, 3H), 7.45−7.53 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 54.3, 87.1, 88.4, 113.0, 114.4, 122.6, 126.9, 127.3, 130.4, 132.0, 158.6.

1-Methoxy-2-(phenylethynyl)benzene (**3ia**).[4b] Colorless oil (75 mg, 90%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.89 (s, 3H), 6.86−6.95 (m, 2H), 7.26−7.35 (m, 4H), 7.49 (dd, J = 1.7, 7.5 Hz, 1H), 7.53−7.58 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.9, 85.8, 93.5, 110.8, 112.5, 120.5, 123.6, 128.1, 128.3, 129.8, 131.7, 133.6, 156.0.

1-Methoxy-2-methyl-4-(phenylethynyl)benzene (**3ja**).[8] Light-yellow solid (88 mg, 99%), mp 84−86 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.20 (s, 3H), 3.83 (s, 3H), 6.77 (d, J = 8.4 Hz, 1H), 7.28−7.39 (m, 5H), 7.47−7.52 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.9, 54.1, 86.6, 88.5, 108.6, 113.6, 122.5, 125.6, 126.6, 127.1, 129.4, 130.2, 132.6, 156.7.

5-Phenylethynylbenzo[1,3]dioxole (**3ka**).[9] White solid (87 mg, 98%), mp 98−100 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.97 (s, 2H), 6.78 (d, J = 7.6 Hz, 1H), 6.98 (d, J = 1.2 Hz, 1H), 7.06 (dd, J = 1.2, 8.2 Hz, 1H), 7.29−7.36 (m, 3H), 7.47−7.52 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 87.5, 89.1, 101.1, 108.3, 111.3, 116.3, 123.1, 126.0, 127.8, 128.1, 131.2, 147.2, 147.7.

1-(Phenylethynyl)naphthalene (**3la**).[4c] Colorless oil (89 mg, 97%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33−7.40 (m, 3H), 7.41−7.46 (m, 1H), 7.48−7.54 (m, 1H), 7.55−7.61 (m, 1H), 7.64 (dd, J = 1.6, 7.7 Hz, 2H), 7.75 (d, J = 6.8 Hz, 1H), 7.83 (t, J = 9.3 Hz, 2H), 8.45 (d, J = 8.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 86.5, 93.3, 119.9, 122.4, 124.3, 125.2, 125.4, 125.8, 127.3, 127.4, 127.4, 127.8, 129.4, 130.7, 132.2, 132.3.

1-Nitro-4-(phenylethynyl)benzene (**3ma**).[10] Light-yellow solid (78 mg, 87%), mp 110−114 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36−7.41 (m, 3H), 7.53−7.57 (m, 2H), 7.62−7.69 (m, 2H), 8.21 (d, J = 8.7 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 86.5, 93.7, 121.1, 122.6, 127.5, 128.3, 129.3, 130.8, 131.3, 146.0.

1-Nitro-3-(phenylethynyl)benzene (**3na**).[6g] Light-yellow solid (86 mg, 96%), mp 68−69 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36−7.40 (m, 3H), 7.52−7.58 (m, 3H), 7.80−7.84 (m, 1H), 8.15−8.19 (m, 1H), 8.37 (t, J = 1.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 86.8, 91.9, 122.1, 122.8, 125.1, 126.3, 128.5, 129.0, 129.3, 131.7, 137.2, 148.1.

1-Nitro-2-(phenylethynyl)benzene (**3oa**).[11] Colorless oil (85 mg, 95%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33−7.38 (m, 3H), 7.40−7.46 (m, 1H), 7.53−7.61 (m, 3H), 7.68 (dd, J = 1.2, 7.8 Hz, 1H), 8.04 (dd, J = 0.7, 8.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 84.8, 97.1, 118.7, 122.4, 124.7, 128.5, 128.6, 129.3, 132.0, 132.8, 134.6, 149.6.

Methyl 4-(Phenylethynyl)benzoate (**3pa**).[4b] Light-yellow solid (94 mg, 99%), mp 114−116 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.93 (s, 3H), 7.37 (t, J = 3.2 Hz, 3H), 7.52−7.57 (m, 2H), 7.59 (d, J = 8.3 Hz, 2H), 8.02 (d, J = 8.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 52.0, 88.4, 92.1, 122.4, 127.8, 128.2, 128.5, 129.2, 129.3, 131.3, 131.5, 166.3.

4-(Phenylethynyl)benzonitrile (**3qa**).[4c] Yellow solid (80 mg, 99%), mp 105−106 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36−7.41 (m, 3H), 7.52−7.57 (m, 2H), 7.58−7.66 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 86.7, 92.8, 110.4, 117.5, 121.2, 127.2, 127.5, 128.1, 130.8, 131.0, 131.1.

1-(2-Phenylethynyl)-4-(trifluoromethyl)benzene (**3ra**).[12] White solid (93 mg, 94%), mp 103−105 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34−7.41 (m, 3H), 7.52−7.57 (m, 2H), 7.58−7.66 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 86.9, 90.7, 121.5, 122.9 (q, J = 270.0 Hz), 124.3 (q, J = 3.8 Hz), 126.1, 127.4, 127.8, 128.9 (q, J = 34.0 Hz), 130.7, 130.8.

3-(Phenylethynyl)pyridine (**3sa**).[4b] Colorless oil (70 mg, 98%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25−7.31 (m, 1H), 7.34−7.40 (m, 3H), 7.52−7.58 (m, 2H), 7.81 (d, J = 7.9 Hz, 1H), 8.55 (d, J = 4.7 Hz, 1H), 8.77 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 84.7, 91.4, 119.3, 121.3, 121.9, 127.3, 127.6, 130.5, 137.2, 147.4, 151.1.

2-(Phenylethynyl)thiophene (**3ta**).[7] Colorless oil (72 mg, 98%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.98−7.02 (m, 1H), 7.25−7.29 (m, 2H), 7.31−7.36 (m, 3H), 7.48−7.54 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 81.6, 92.0, 121.9, 122.2, 126.1, 126.2, 127.3, 127.4, 130.4, 130.9.

Methyl 5-(Phenylethynyl)thiophene-2-carboxylate (**3ua**).[13] Yellow solid (91 mg, 94%), mp 70−72 °C; ^{1}H NMR ($CDCl_3$) δ 3.89 (s, 3H), 7.28 (d, J = 3.8 Hz, 1H), 7.34−7.38 (m, 3H), 7.49−7.56 (m,

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2H), 7.68 (d, J = 3.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 52.3, 82.0, 95.7, 122.2, 128.5, 129.1, 130.1, 131.6, 132.2, 133.3, 133.8, 162.0.

*Methyl 3-(Phenylethynyl)thiophene-2-carboxylate (**3va**).*[14] Colorless oil (94 mg, 97%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.92 (s, 3H), 7.19 (d, J = 6.3 Hz, 1H), 7.32−7.37 (m, 3H), 7.44 (d, J = 5.1 Hz, 1H), 7.55−7.61 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 52.2, 84.0, 95.4, 123.0, 127.5, 128.4, 128.8, 130.5, 131.9, 132.1, 133.4, 161.9.

*1-Methoxy-4-(4-tolylethynyl)benzene (**3hb**).*[10] Light-yellow solid (88 mg, 99%), mp 119−122 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.36 (s, 3H), 3.82 (s, 3H), 6.87 (d, J = 8.4 Hz, 2H), 7.14 (d, J = 7.6 Hz, 2H), 7.40 (d, J = 8.0 Hz, 2H), 7.46 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5, 54.3, 87.2, 87.6, 113.0, 114.6, 119.5, 128.1, 130.3, 132.0, 137.0, 158.5.

*1-((4-Methoxyphenyl)ethynyl)-3-methylbenzene (**3hc**).*[5c] Yellow solid (85 mg, 96%), mp 43−45 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.33 (s, 3H), 3.79 (s, 3H), 6.83−6.88 (m, 2H), 7.11 (d, J = 7.6 Hz, 1H), 7.21 (t, J = 7.6 Hz, 1H), 7.29−7.35 (m, 2H), 7.43−7.48 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.0, 55.0, 88.0, 88.8, 113.8, 115.2, 123.2, 128.0, 128.3, 128.6, 131.8, 132.8, 137.7, 159.3.

*1-((4-Methoxyphenyl)ethynyl)-2-methylbenzene (**3hd**).*[6g] Light-yellow solid (68 mg, 76%), mp 74−75 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.50 (s, 3H), 3.80 (s, 3H), 6.87 (d, J = 8.8 Hz, 2H), 7.12−7.23 (m, 3H), 7.44−7.50 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5, 55.1, 86.8, 93.1, 113.8, 115.4, 123.1, 125.3, 127.8, 129.2, 131.4, 132.7, 139.7, 159.3.

*2-((4-Methoxyphenyl)ethynyl)-1,3-dimethylbenzene (**3he**).*[15] Yellow solid (41 mg, 42%), mp 70−71 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.43 (s, 6H), 3.76 (s, 3H), 6.81 (d, J = 8.7 Hz, 2H), 6.94−7.08 (m, 3H), 7.40 (d, J = 8.7 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.2, 55.4, 85.8, 97.8, 114.0, 116.0, 123.3, 126.7, 127.4, 132.8, 140.0, 159.5.

*1,2-Bis(4-methoxyphenyl)ethyne (**3hf**).*[7] Light-yellow solid (89 mg, 93%), mp 143−145 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.82 (s, 6H), 6.84−6.89 (m, 4H), 7.42−7.47 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 54.3, 86.9, 112.9, 114.7, 131.9, 158.4.

*5-((4-Methoxyphenyl)ethynyl)benzo[1,3]dioxole (**3hg**).*[9] Yellow solid (94 mg, 93%), mp 123−125 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.81 (s, 3H), 5.97 (s, 2H), 6.77 (d, J = 8.0 Hz, 1H), 6.86 (d, J = 8.4 Hz, 2H), 6.96 (d, J = 0.9 Hz, 1H), 7.00−7.05 (m, 1H), 7.44 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.0, 87.5, 87.7, 101.0, 108.2, 111.2, 113.7, 115.2, 116.6, 125.8, 132.7, 147.2, 147.4, 159.2.

*1-(4-((4-Methoxyphenyl)ethynyl)phenyl)ethanone (**3hh**).*[16] White solid (78 mg, 78%), mp 125−128 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.61 (s, 3H), 3.84 (s, 3H), 6.90 (d, J = 8.4 Hz, 2H), 7.49 (d, J = 8.8 Hz, 2H), 7.58 (d, J = 8.0 Hz, 2H), 7.93 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 26.4, 55.1, 87.3, 92.7, 113.9, 114.4, 128.0, 128.4, 131.2, 133.0, 135.6, 159.8, 197.1.

*Methyl 2-((4-Methoxyphenyl)ethynyl)benzoate (**3hi**).*[17] Colorless oil (62 mg, 58%); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.76 (s, 3H), 3.89 (s, 3H), 6.82 (d, J = 8.8 Hz, 2H), 7.24−7.32 (m, 1H), 7.35−7.49 (m, 3H), 7.55 (d, J = 7.5 Hz, 1H), 7.89 (d, J = 7.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 52.2, 55.3, 87.1, 94.6, 114.0, 115.4, 124.1, 127.5, 130.5, 131.6, 131.7, 133.3, 133.8, 159.9, 166.8.

*1-Methoxy-4-((4-nitrophenyl)ethynyl)benzene (**3hj**).*[10] Yellow solid (76 mg, 75%), mp 110−111 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.85 (s, 3H), 6.91 (d, J = 8.8 Hz, 2H), 7.50 (d, J = 8.8 Hz, 2H), 7.63 (d, J = 8.4 Hz, 2H), 8.20 (d, J = 8.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 28.7, 54.3, 85.6, 94.1, 113.2, 122.6, 129.7, 131.0, 132.4, 145.7, 159.4.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Copies of NMR spectra for all of the compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Authors

*Fax: (+86)-371-6797-9408. E-mail: yangf@zzu.edu.cn.

*E-mail: wyj@zzu.edu.cn.

Notes

The authors declare no competing financial interest.

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