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A Suzuki-type cross-coupling reaction of arylacetylene halides with arylboronic acids

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A $PdCl_2$-catalyzed direct alkynylation of arylboronic acids to give diarylacetylenes is described. The optimal conditions using $PdCl_2$ as catalyst, MeOH–PhMe–H_2O as solvent and K_2CO_3 as base effectively suppressed the formation of homo-coupling product and afforded moderate to good yield of the desired unsymmetrical coupling product. This reaction represents a Suzuki-type sp^2(C–B)–sp(C–X) cross-coupling.

Supporting information may be found in the online version of this article.

Keywords: Suzuki cross-coupling; diarylacetylene; palladium chloride; alkynylation

Introduction

The palladium-catalyzed Suzuki cross-coupling reaction between different types of organoboron compounds and organic halides or triflates provides a powerful and useful synthetic methodology for the formation of carbon–carbon bonds. The new protocols related to this cross-coupling reaction have been reported continuously since its discovery. Originally, sp^2–sp^2 C–C coupling leading to the diaryl compounds dominated Suzuki coupling. Later on, the scope of the Suzuki reaction was extended, and recently its ability to couple aryl or alkyl boron compounds with sp^3-hybridized alkyl halides to form sp^2–sp^3 and sp^3–sp^3 C–C bonds has been extensively explored.[1] Generally, the organoboron compounds could be (hetero)aryl, alkenyl, alkyl and even alkynylboronic acid, but the choice of the electrophilic partner was limited to (hetero)aryl, vinylic and alkyl halides. The employment of alkynyl iodide in the coupling reaction was a great challenge because of the cross-homo scrambling, and there have been no reports on this kind of coupling reaction. There have been few reports on the sp^2–sp C–C bond formation by coupling of sp C–X bonds and sp^2 C–B bonds[2] compared with sp^2 or sp^3 C–X (X = halogen) substrates employed to couple with organoboron derivatives.

In recent years, diarylacetylenes have received a great deal of attention owing to their spectroscopic and electronic properties[3] as well as their biological activities.[4] In addition to the traditional elimination and alkylation reactions, there are many other approaches to synthesize diarylacetylenes, such as alkyne metathesis,[5] Seyferth–Gilbert homologation[6] and Castro–Stephens coupling.[7] The most direct and powerful synthetic strategies for the diarylacetylenes formation is the Sonogashira coupling reaction,[8] which is a Pd-catalyzed cross coupling of an aryl halide with a terminal acetylene. However, this method has some limitations,[9] for example, giving low yields or requiring high reaction temperatures in some cases. Therefore, alternative Pd-catalyzed alkynylation protocols have been established. For instance, besides the well-known Negishi cross-coupling reactions,[10] the alkynyltrifluoroborate reagents[9] developed by Molander and alkynyldimethylalminum reagents by Micouin[11] provide other strategies for the sp^2–sp C–C bond formations. However, the requirement for substrate activation by organometallics renders the process uneconomical. In a previous communication,[12] we reported a new approach to the synthesis of diarylacetylenes by the coupling of arylacetylene iodides and arylboronic acids. We have since extended this reaction to arylacetylene bromides and here disclose this type of Suzuki cross-coupling (sp^2–sp) from haloalkynes (iodo and bromo) and arylboronic acids to form diarylacetylenes, and describe further details on the process.

Results and Discussion

This study originated from our past work on polysubstituted pyrroles, which has been described in a previous paper.[13] Pyrrole **3** was one of the target molecules of the 2,3,4-trisubstituted pyrrole **1** (Scheme 1). Originally, we attributed the value at δ 0.33 to the TMS(trimethylsilyl) attached to the triple bond bases on the ^{1}H NMR. It seems that the trimethylsilyl group on C-3 of pyrrole **1** was replaced by the *p*-methoxyphenyl to form **3** through iodination and subsequent Suzuki cross-coupling reaction. However, further study revealed that this structural assignment was incorrect. The correct structure was established by X-ray crystallography and designated as compound **5**. Our analysis displayed iodination and subsequent coupling took place, but iodination occurred on the

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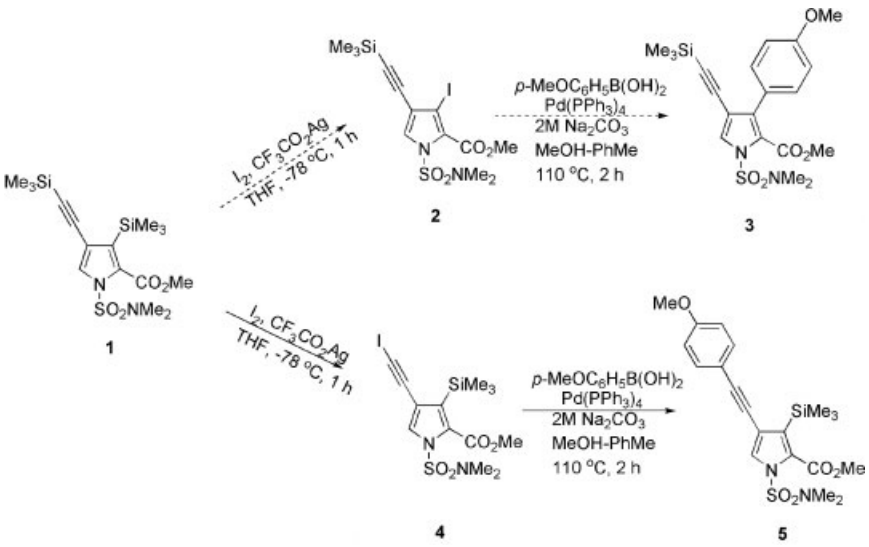


Scheme 1. The transformation from pyrrole **1** to pyrrole**3**.

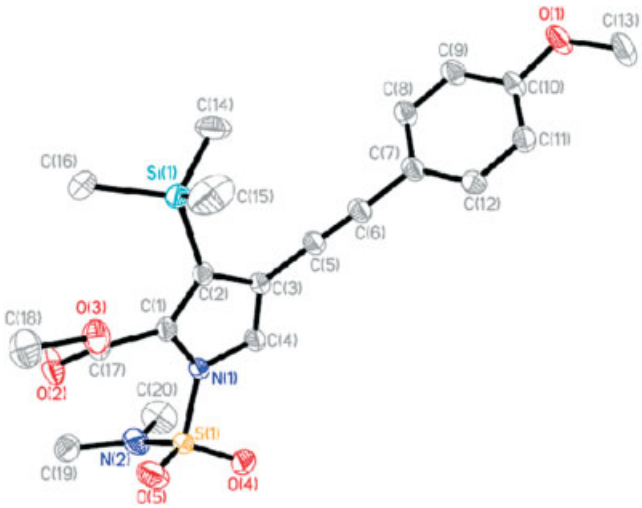
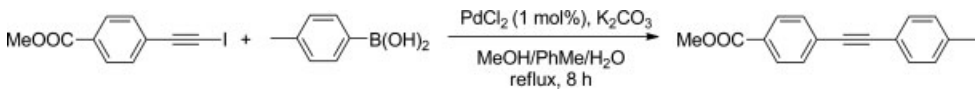


Figure 1. Molecular structure of pyrrole **5** drawn at the 30% probability level with ORTEP-3.[14].

TMS attached to the triple bond with the result of a new kind of coupling reaction between alkynyl iodide and phenylboronic acid, which has not been systematically studied before. Selective iodination and arylboronic acid coupling with the iodide on the sp carbon atom are two significant features for this transformation. As far as we know, this is the first case of a 1-iodo-2-arylalkyne coupling with arylboronic acid to form a diarylacetylene under Suzuki-type conditions.

From the single crystal X-ray diffraction structure of **5** (Fig. 1), which was drawn with 30% displacement ellipsoids using ORTEP-3,[14] we can see that the atoms adjacent to the pyrrole (C5, C17 and Si1) are in the plane of the pyrrole ring, which is confirmed by the sum of the angles around the carbon atoms with substituted groups in the pyrrole: 359.8(5)°, 359.7(5)° and 359.9(5)°, respectively. However, the S1 atom is out of the plane of the pyrrole ring with the sum of the angles around N1 being 316.5(4)°. The phenyl and the pyrrolyl groups are co-linear because of the rigidity of the connecting ethynyl group, and the rings are approximately orthogonal to each other.

Based on this unexpected result, we were interested to see if other substrates could be applied under the same conditions: $Pd(PPh_3)_4$, Na_2CO_3, MeOH(methanol)–PhMe(toluene)–H_2O and reflux. Different substrates were tried under this catalytic system, but the yield of cross-coupling products was not satisfactory. We began to explore the conditions to optimize the reaction by using (*p*-methoxycarbonylphenyl)ethynyl iodide and *p*-methylphenyl boronic acid as reaction partners in the reaction (Scheme 2). We modified the reaction conditions with respect to four key variables: the catalyst system, the solvent system, the base and the amount of substrates. Of the different palladium catalysts examined, including $Pd(PPh_3)_4$, $Pd(PPh_3)_2Cl_2$, $Pd(OAc)_2$ and $PdCl_2$, the best result was obtained using $PdCl_2$ (1 mol%). The most suitable solvent system for this transformation was the typical solvent mixture widely used in Suzuki coupling reaction: MeOH–toluene–H_2O (3 : 3:1). The solvents MeOH, THF(tetra hydro furan) and THF–water were found to be less effective. Usually, when the reaction proceeded in a weak polar solvent with Pd^0 complex as catalyst, the major product would be the homo-coupling product of the arylacetylene iodides. When the Pd^{II} complex catalyst was added, homo-coupling of arylboronic acids predominated. All of the organic and inorganic bases, K_2CO_3, CH_3ONa, NaOH, Et_3N and K_3PO_4, gave good yields. The amount of *p*-methylphenylboronic acid is crucial, and when it was raised to 1.5 equiv., the yield of the coupling products was substantially increased by circumventing homo-dimerization from arylboronic acid. A greater amount of boronic acid (2 or 3 equiv.) did not improve the yield. Thus, the best result (yield of 88%)



Scheme 2. The optimized conditions to couple arylacetylene iodides with arylboronic acids.

was obtained when $PdCl_2$ (1 mol%) was employed as catalyst, MeOH–toluene–H_2O (3 : 3:1) as solvent, K_2CO_3 (2 M) as base, and 1.5 equiv. *p*-methylphenylboronic acid with refluxing at 80 °C for 8 h.

Under the optimal conditions, the experimental scope was extended to other arylacetylene iodides and arylboronic acids (Table 1). The aryl subunit on arylethynyl iodide can tolerate different types of substituents: phenyl rings with electron-deficient groups such as *para*-substituted -CO_2Me, -CHO, -COMe and -CN, and *ortho*-substituted -CF_3 gave good to high yields (83–92%, entries 1–5); phenyl rings containing electron-rich substituents such as *para*-Me and -OMe also reacted well, giving yields of 82 and 79%, respectively (entries 7 and 8), but they were not as reactive as the electron-deficient substrates and more catalyst (5 mol%) was needed. When iodoethynyl-benzene was employed, the yield was 74% (entry 6). *Ortho*-substituted arylethynyl iodides were used with good results, with *ortho*-CF_3 and -CHO groups affording yields of 83 and 82%, respectively (entries 5 and 12). Replacing the aryl group of an arylacetylene iodide with a heteroaryl gave satisfactory results. For example, furan, thiophene and benzo[1,3]dioxole-containing substrates bearing electron-withdrawing groups (-CHO, -COOMe) gave yields ranging from 82 to 91% (entries 9–12). These heterocyclic cross coupling products are new compounds which have not been reported before. Pyridine-containing arylacetylene iodides were not employed in the reaction because of their sensitivity to light and heat during the preparation. When a variety of substituted phenylboronic acids such as naphthyl, 4-methoxyphenyl, 2-hydroxyphenyl, phenyl, 4-fluorophenyl and 2,4,6-trichloro-phenylboronic acid were used as the substrate (entries 13–19), a lower yield was observed with the bulky naphthyl boronic acid (69%, entry 13), but acceptable to good yields were obtained not only for electron-rich borolanes bearing -OMe and -OH (entries 14–16), and for electronically neutral phenylboronic acid (entry 17), but also for electron-poor systems with F and Cl (entries 18 and 19). However, with substituents in the *ortho* position of the aryl rings, the reactants showed relatively less activity because of steric hindrance (entries 16 and 19). With the *p*-fluorophenyl and 2,4,6-trichlorophenylboronic acids, the reaction gave inseparable mixtures consisting of both cross-coupling and homo-coupling products, the latter being a minor by-product which has the same R_f value as the desired cross-coupling product. Thus, the yields are given based on the ^{1}H NMR spectra. We can see that this catalytic system allows a diverse range of electron density around the aromatic rings either from arylacetylene iodides or aryl boronic acids.

We were curious whether these optimized conditions could be applied to brominated terminal alkynes. The reactions of *p*-methylphenyl boronic acid with arylacetylene bromides were first examined. The results are shown in Table 2. The reaction of arylacetylene bromides with 1.5 equiv. of *p*-methylphenylboronic acid gave the desired coupling product (entry 1). Similarly, *p*-CHO, *p*-COMe, and *p*-CN substituted phenyl analogs gave the expected products in comparable yields (entries 2–4). However, when the electron-withdrawing -CF_3 group was in the *ortho* position on the phenyl ring, the yield decreased slightly (entry 5). Heterocyclic systems were also investigated. Thiophene and furan rings containing electron-withdrawing groups -CHO and -COMe underwent smooth transformation in good yields (entries 6 and 7). Next, we investigated different boronic acids. Employment of 2-naphthylboronic acid led to markedly reduced yield owing to the steric hindrance (entry 8). When we used the less reactive *p*-fluoro or 2,4,6-trichloroboronic acid as reactants while keeping electron-withdrawing substituents on the phenyl ring of the alkynyl bromide, acceptable yields were obtained (entries 9–11). Usually, the yields of cross-coupling products were almost the same as that of the iodide analogue (Table 1). Different arylacetylene bromides with electron-withdrawing groups on the phenyl or heterocyclic subunit reacted smoothly with 1.5 equiv. *p*-methylphenylboronic acid (Table 2, entries 1–7). However, when arylacetylene bromides containing electron-rich substrates were used, the reactions did not proceed even with 5 mol% catalyst in 24 h (entries 12 and 13).

In most cases the yields obtained from the protocol outlined in this paper are comparable to those obtained by the Sonogashira reaction;[15] however, in some cases the yields from our protocol are superior. One example involved the reaction of 4-(2-iodoethynyl)benzaldehyde with *p*-methylphenylboronic acid for the preparation of 4-[2-(4-methylphenyl)ethynyl] benzaldehyde (entry 2 in Tables 1 and 2). Much improved yields (84 and 83% respectively) were achieved compared with the result (31%) obtained by ordinary Sonogashira coupling.[16] Although a high yield of this product was recently reported by Sonogashira coupling, an unusual N-heterocyclic carbene precatalyst was required, which has a complicated structure and requires a multi-step synthesis.[17] Some other -CHO group-containing products were also prepared in good to high yields, the results indicating that -CHO group can facilitate the cross coupling reaction in this system. In the Sonogashira reaction, the acetylene subunit of the diarylacetylene comes from the nucleophile, whereas with our method the acetylene subunit comes from the electrophile. The change of the acetylene subunit from nucleophile to electrophile makes this method a supplement of the Sonogashira reaction to synthesize diarylacetylenes.

Conclusion

We have established a new protocol for the preparation of diarylacetylenes, and demonstrated the ability of sp–C halides to couple with sp^2–C boronic acids. This is an important addition to the well-known Suzuki cross-coupling reaction. This process offers broad scope with respect to both the alkynyl halides and arylboronic acids by allowing a wide range of electron density on the aromatic rings. The change of the arylacetylene subunit from nucleophile to electrophile makes this method a supplement to the Sonogashira reaction.

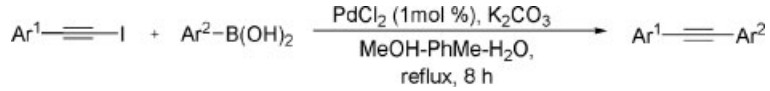
Experimental Section

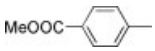
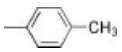
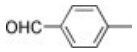
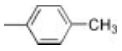
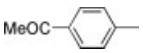
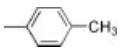
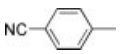
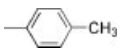
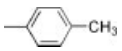
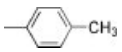
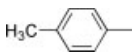
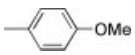
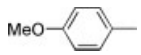
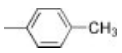
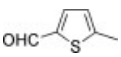
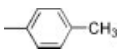
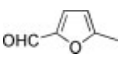
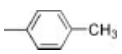
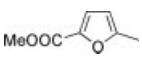
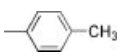
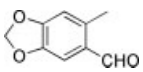
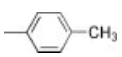
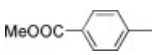
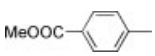
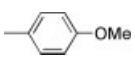
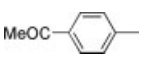
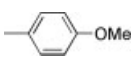
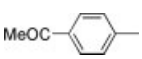
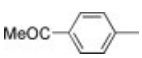
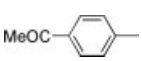
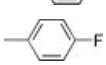
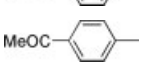
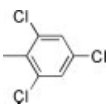
All arylacetylene iodides,[18] arylacetylene bromides[19] and some arylboronic acids[20] were prepared according to literature procedures. All of the compounds synthesized were characterized by ^{1}H, ^{13}C NMR and mass spectrometry.

General Procedure for the Synthesis of the Diarylacetylenes

Haloethynyl aryl substrate (0.2 mmol), arylboronic acid (0.3 mmol), $PdCl_2$ (0.35 mg, 0.002 mmol) and K_2CO_3 (55.2 mg, 0.4 mmol) were added to a solution of 7 ml MeOH–toluene–H_2O (3 : 3:1). The resulting mixture was stirred and heated at ca. 80 °C for 8 h and then cooled to room temperature. The mixture was extracted with Et_2O (2 × 20 ml), washed with H_2O (15 ml), dried (Na_2SO_4), filtered and evaporated, and the residue was purified by chromatography on silica gel to give the cross coupling product as crystals.

Table 1. Coupling of arylacetylene iodides and arylboronic acids



Entry	Ar^1	Ar^2	Isolated yield (%)
1			88
2			84[a]
3			92
4			85[a]
5			83[b]
6			74[b,c]
7			82[d]
8			79[d]
9			91
10			86
11			89
12			82
13			69
14			82
15			84
16			73
17			78
18			84
19			79[b]

[a] The solvent was THF–MeOH–H_2O. [b] Yield determined by ^1H NMR. [c] The catalyst amount was 2.5 mol%. [d] The catalyst amount was 5 mol%.

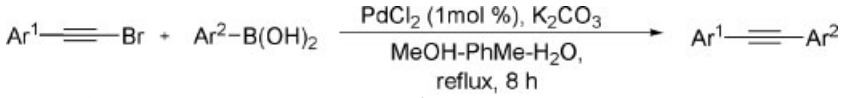
4-[2-(4-Methylphenyl)ethynyl]benzoic Acid Methyl Ester

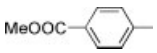
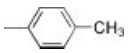
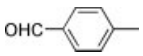
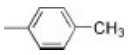
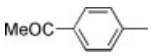
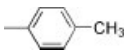
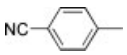
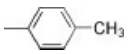
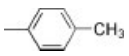
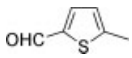
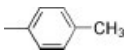
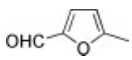
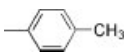
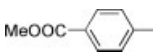
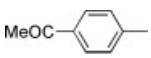
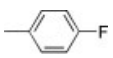
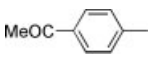
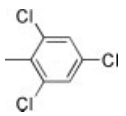
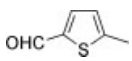
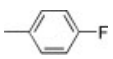
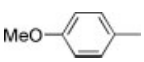
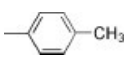
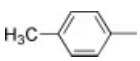
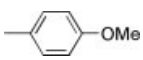
Yield 44 mg, 88%; pale-yellow crystals, m.p.: 134–136 °C. ^1H NMR ($CDCl_3$) δ 2.37 (s, 3H, CH_3), 3.92 (s, 3H, CH_3), 7.17 (d, J = 8 Hz, 2H, CH), 7.44 (d, J = 8 Hz, 2H, CH), 7.57 (d, J = 8.4 Hz, 2H, CH), 8.01 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 21.7 (CH_3), 52.4 (CH_3), 88.2 (C≡C), 92.8 (C≡C), 119.8 (aromatic C), 128.4 (aromatic C), 129.4 (aromatic C), 129.6 (aromatic C), 129.7 (aromatic C), 131.6 (aromatic C), 131.8 (aromatic C), 139.2 (aromatic C), 166.8 (CO). GC/TOF HRMS-EI: calcd for $C_{13}H_{14}O_2$, 250.0994; found 250.0993.

4-[2-(4-Methylphenyl)ethynyl]benzaldehyde

White crystals, m.p.: 118–123 °C. ^1H NMR ($CDCl_3$) δ 2.41 (s, 3H, CH_3), 7.28 (d, J = 8.4 Hz, 2H, CH), 7.53 (d, J = 8 Hz, 2H, CH), 7.73 (d, J = 8 Hz, 2H, CH), 7.92 (d, J = 8.4 Hz, 2H, CH), 10.05 (s, 1H, CHO). ^{13}C NMR ($CDCl_3$) δ 21.3 (CH_3), 127.4 (aromatic C),

Table 2. Coupling of arylacetylene bromides and arylboronic acids



Entry	Ar^1	Ar^2	Isolated yield (%)
1			85
2			83
3			88
4			85
5			76[a]
6			82
7			84
8			49
9			71
10			69[a]
11			78
12			0
13			0

[a] Yield determined by ^{1}H NMR.

127.6 (aromatic C), 129.9 (aromatic C), 130.4 (aromatic C), 135.1 (aromatic C), 136.9 (aromatic C), 138.7 (aromatic C), 147.3 (aromatic C), 192.1 (CHO). GC/TOF HRMS-EI: calcd for $C_{16}H_{12}O$, 220.0888; found 220.0894.

1-{4-[2-(4-Methylphenyl)ethynyl]phenyl}ethanone

Yellow crystals, m.p.: 130–132 °C. ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H, CH_3), 2.62 (s, 3H, CH_3), 7.18 (d, J = 8 Hz, 2H, CH), 7.48 (d, J = 8 Hz, 2H, CH), 7.60 (d, J = 8.4 Hz, 2H, CH), 7.94 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 21.7 (CH_3), 26.8 (CH_3), 88.2 (C≡C), 93.2 (C≡C), 119.7 (aromatic C), 128.4 (aromatic C), 128.6 (aromatic C), 129.4 (aromatic C), 131.8 (aromatic C), 131.8 (aromatic C), 136.2 (aromatic C), 139.3 (aromatic C), 197.5 (CN). API-ES: calcd for $C_{17}H_{14}O$, 234.1045; found 235.2 $[M + H]^+$.

4-[2-(4-Methylphenyl)ethynyl]benzonitrile

Yellow crystals, m.p.: 162–164 °C. ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H, CH_3), 7.18 (d, J = 8 Hz, 2H, CH), 7.43 (d, J = 8 Hz, 2H, CH), 7.58 (d, J = 8.4 Hz, 2H, CH), 7.62 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 21.8 (CH_3), 87.4 (C≡C), 94.3 (C≡C), 111.4 (CN), 118.8 (aromatic C), 119.3 (aromatic C), 128.7 (aromatic C), 129.5 (aromatic C), 131.9 (aromatic C), 132.2 (aromatic C), 132.2 (aromatic C), 139.6 (aromatic C). GC/TOF HRMS-EI: calcd for $C_{16}H_{11}N$, 217.0891; found 217.0882.

2-[2-(4-Methylphenyl)ethynyl]benzotrifluoride

Mixure of the product and 4,4′-dimethyl-biphenyl, white crystals, ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H, CH_3), 7.16 (d, J = 8 Hz, 2H, CH), 7.38 (t, J = 7.6 Hz, 1H, CH), 7.47 (d, J = 8 Hz, 2H, CH), 7.49 (t, J = 8 Hz, 1H, CH), 7.64 (d, J = 8.8 Hz, 1H, CH), 7.66 (d, J = 8.4 Hz, 1H, CH). GC/TOF HRMS-EI: calcd for $C_{16}H_{11}F_3$, 260.0813; found 260.0822.

1-Methyl-4-phenylethynylbenzene

Because of the difficulties in separation, we only obtained the mixture of the product and the byproduct 4,4′-dimethyl-biphenyl. ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H, CH_3), 7.15(d, J = 8 Hz, 2H, CH), 7.31–7.36 (m, 3H, Ph), 7.47 (d, J = 8.4 Hz, 2H, CH), 7.52 (d, J = 8.4 Hz, 2H, CH). GC/TOF HRMS-EI: calcd for $C_{15}H_{12}$,192.0939; found 192.0948.

1-{4-[2-(4-Methylphenyl)ethynyl]phenyl}methyl Ether

Pale-yellow crystals, m.p.: 120–124 °C. ^{1}H NMR ($CDCl_3$) δ 2.36 (s, 3H, CH_3), 3.82 (s, 3H, CH_3), 6.87 (d, J = 8.8 Hz, 2H, CH), 7.14 (d, J = 8 Hz, 2H, CH), 7.40 (d, J = 8 Hz, 2H, CH), 7.46 (d, J = 8.8 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 21.7 (CH_3), 55.5 (CH_3), 88.4 (C≡C), 88.9 (C≡C), 114.2 (aromatic C), 115.8 (aromatic C), 120.7 (aromatic C), 129.3 (aromatic C), 131.5 (aromatic C), 133.2 (aromatic C), 138.2 (aromatic C), 159.7 (aromatic C). API-ES: calcd for $C_{16}H_{14}O$, 222.1045; found 223.1 $[M + H]^+$.

5-*p*-Tolylethynyl-thiophene-2-carbaldehyde

Yellow crystals, m.p.: 136–138 °C. ^{1}H NMR (acetone-d_6) δ 2.38 (s, 3H, CH_3), 7.28 (d, J = 8 Hz, 2H, CH), 7.47 (d, J = 3.6 Hz, 1H, CH), 7.48 (d, J = 8 Hz, 2H, CH), 7.94 (d, J = 4 Hz, 1H, CH), 9.95 (s, 1H, CHO). ^{13}C NMR (acetone-d_6) δ 20.6 (CH_3), 81.0 (C≡C), 97.9 (C≡C), 118.7 (aromatic C), 129.4 (aromatic C), 131.5 (aromatic C), 131.5 (aromatic C), 133.0 (aromatic C), 137.0 (aromatic C), 140.0 (aromatic C), 144.3 (aromatic C), 182.8 (CHO). GC/TOF HRMS-EI: calcd for $C_{14}H_{10}OS$, 226.0452; found 226.0459.

5-*p*-Tolylethynyl-furan-2-carbaldehyde

Yellow crystals, m.p.: 97–100 °C. ^{1}H NMR ($CDCl_3$) δ 2.39 (s, 3H, CH_3), 6.75 (d, J = 3.6 Hz, 1H, CH), 7.19 (d, J = 7.6 Hz, 2H, CH), 7.25 (d, J = 4 Hz, 1H, CH), 7.44 (d, J = 8 Hz, 2H, CH), 9.63 (s, 1H, CHO). ^{13}C NMR ($CDCl_3$) δ 21.6 (CH_3), 78.0 (C≡C), 96.8 (C≡C), 116.7 (aromatic C), 118.1 (aromatic C), 129.3 (aromatic C), 131.7 (aromatic C), 140.1 (aromatic C), 142.3 (aromatic C), 152.3 (aromatic C), 177.2 (CHO). API-ES: calcd for $C_{14}H_{10}O_2$, 210.0681; found 211.1 $[M + H]^+$.

5-*p*-Tolylethynyl-furan-2-carboxylic Acid Methyl Ester

Yellow crystals, m.p.: 105–107 °C. ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H, CH_3), 3.92 (s, 3H, CH_3), 6.67 (d, J = 3.6 Hz, 1H, CH), 7.17 (d, J = 7.6 Hz, 2H, CH), 7.19 (d, J = 3.6 Hz, 1H, CH), 7.43 (d, J = 8 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 21.6 (CH_3), 52.1 (CH_3), 78.0 (C≡C), 95.3 (C≡C), 116.2 (aromatic C), 118.4 (aromatic C), 118.9 (aromatic C), 129.3 (aromatic C), 131.6 (aromatic C), 139.7 (aromatic C), 140.6 (aromatic C), 144.2 (aromatic C), 158.5 (CO). API-ES: calcd for $C_{15}H_{12}O_3$, 240.0786; found 241.1 $[M + H]^+$.

6-*p*-Tolylethynyl-benzo[1,3]dioxole-5-carbaldehyde

Yellow crystals, m.p.: 145–148 °C. ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H, CH_3), 6.07 (s, 2H, CH_2), 7.00 (s, 1H, CH), 7.17 (d, J = 8 Hz, 2H, CH), 7.35 (s, 1H, CH), 7.42 (d, J = 8 Hz, 2H, CH), 10.48 (s, 1H, CHO). ^{13}C NMR ($CDCl_3$) δ 21.6 (CH_3), 84.2 (C≡C), 95.4 (C≡C), 102.4 (CH_2), 106.0 (aromatic C), 111.9 (aromatic C), 119.3 (aromatic C), 123.9 (aromatic C), 129.3 (aromatic C), 131.5 (aromatic C), 132.0 (aromatic C), 139.3 (aromatic C), 148.5 (aromatic C), 152.4 (aromatic C), 190.1 (CHO). GC/TOF HRMS-EI: calcd for $C_{17}H_{12}O_3$, 264.0786; found 264.0796.

4-Naphthalen-1-ylethynyl-benzoic Acid Methyl Ester

Brown crystals, m.p.: 109–113 °C. ^{1}H NMR ($CDCl_3$) δ 3.93 (s, 3H, CH_3), 7.46 (t, J = 8 Hz, 1H, CH), 7.54 (t, J = 7.4 Hz, 1H, CH), 7.61 (t, J = 6.8 Hz, 1H, CH), 7.69 (d, J = 8.4 Hz, 2H, CH), 7.78 (dd, J = 7.2 Hz, J = 4 Hz, 1H, CH), 7.86 (d, J = 8 Hz, 2H, CH), 8.06 (d, J = 8.4 Hz, 2H, CH), 8.41 (d, J = 8.4 Hz, 1H, CH). ^{13}C NMR ($CDCl_3$) δ 52.4 (CH_3), 90.7 (C≡C), 93.6 (C≡C), 120.4 (aromatic C), 125.4 (aromatic C), 126.2 (aromatic C), 126.7 (aromatic C), 127.1 (aromatic C), 128.3 (aromatic C), 128.5 (aromatic C), 129.5 (aromatic C), 129.7 (aromatic C), 129.7 (aromatic C), 130.9 (aromatic C), 131.7 (aromatic C), 133.4 (aromatic C), 166.7 (CO). GC/TOF HRMS-EI: calcd for $C_{20}H_{14}O_2$, 286.0994; found 286.1000.

4-(4-Methoxyphenylethynyl)benzoic Acid Methyl Ester

Pale-yellow crystals, m.p.: 156–158 °C. ^{1}H NMR ($CDCl_3$) δ 3.83 (s, 3H, CH_3), 3.92 (s, 3H, CH_3), 6.89 (d, J = 8.8 Hz, 2H, CH), 7.48 (d, J = 8.8 Hz, 2H, CH), 7.56 (d, J = 8 Hz, 2H, CH), 8.00 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 52.3 (CH_3), 55.5 (CH_3), 87.7 (C≡C), 92.7 (C≡C), 114.3 (aromatic C), 114.9 (aromatic C), 128.6 (aromatic C), 129.3 (aromatic C), 129.6 (aromatic C), 131.4 (aromatic C), 133.4 (aromatic C), 160.2 (aromatic C), 166.8 (CO). API-ES: calcd for $C_{17}H_{14}O_3$, 266.0943; found 267.4 $[M + H]^+$.

1-[4-(4-Methoxyphenylethynyl)-phenyl]ethanone

Yellow crystals, m.p.: 128–131 °C. ^{1}H NMR ($CDCl_3$) δ 2.61 (s, 3H, CH_3), 3.84 (s, 3H, CH_3), 6.90 (d, J = 9.2 Hz, 2H, CH), 7.49 (d, J = 8.8 Hz, 2H, CH), 7.58 (d, J = 8.4 Hz, 2H, CH), 7.93 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 26.5 (CH_3), 55.3 (CH_3), 87.5 (C≡C), 92.9 (C≡C), 114.1 (aromatic C), 114.7 (aromatic C), 128.2 (aromatic C), 128.6 (aromatic C), 131.4 (aromatic C), 133.2 (aromatic C), 135.9 (aromatic C), 160.1 (aromatic C), 197.3 (CO). API-ES: calcd for $C_{17}H_{14}O_2$, 250.0994; found 251.1 $[M + H]^+$.

1-[4-(2-Hydroxyphenylethynyl)phenyl]ethanone

Pale-yellow crystals, m.p.: 170–175 °C. ^{1}H NMR ($CDCl_3$) δ 2.63 (s, 3H, CH_3), 7.26 (t, J = 7.2 Hz, 1H, CH), 7.33 (t, J = 8 Hz, 1H, CH), 7.54 (d, J = 8 Hz, 1H, CH), 7.61 (d, J = 7.6 Hz, 1H, CH), 7.94 (d, J = 8.4 Hz, 2H, CH), 8.03 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 26.8 (CH_3), 103.8 (C≡C), 111.5 (C≡C), 121.5 (aromatic C), 123.4 (aromatic C), 124.9 (aromatic C), 125.3 (aromatic C), 129.0 (aromatic C), 129.1 (aromatic C), 134.7 (aromatic C), 136.7 (aromatic C), 154.7 (aromatic C), 155.4 (aromatic C), 197.5 (CO). API-ES: calcd for $C_{16}H_{12}O_2$, 236.0837; found 237.1 $[M + H]^+$.

1-(4-Phenylethynyl-phenyl)ethanone

Pale-yellow crystals, m.p.: 95–98 °C. ^{1}H NMR ($CDCl_3$) δ 2.60 (s, 3H, CH_3), 7.35–7.37 (m, 3H, Ph), 7.54–7.56 (m, 2H, Ph), 7.60 (d, J = 8.4 Hz, 2H, CH), 7.93 (d, J = 8.4 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 26.7 (CH_3), 88.7 (C≡C), 92.9 (C≡C), 122.8 (aromatic C), 128.3 (aromatic C), 128.4 (aromatic C), 128.6 (aromatic C), 128.9 (aromatic C), 131.8 (aromatic C), 131.9 (aromatic C), 136.3 (aromatic C), 197.4 (CO). API-ES: calcd for $C_{16}H_{12}O_2$, 220.0888; found 221.1 $[M + H]^+$.

1-[4-(4-Fluorophenylethynyl)phenyl]ethanone

Yellow crystals, m.p.: 105–107 °C. ^{1}H NMR ($CDCl_3$) δ 2.63 (s, 3H, CH_3), 7.08 (t, J = 8 Hz, 2H, CH), 7.55 (dd, J = 8.4 Hz, J = 5.2 Hz, 2H, CH), 7.61 (d, J = 8.4 Hz, 2H, CH), 7.95 (d, J = 8 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$) δ 26.7 (CH_3), 88.4 (C≡C), 88.5 (C≡C), 91.7 (C≡C), 115.8 (aromatic C), 116.1 (aromatic C), 118.9 (aromatic C), 118.9 (aromatic C), 128.1 (aromatic C), 128.4 (aromatic C), 131.8 (aromatic C), 133.8 (aromatic C), 133.9 (aromatic C), 136.4 (aromatic C), 161.7 (aromatic C), 164.2 (aromatic C), 197.4 (CO). API-ES: calcd for $C_{16}H_{11}FO$, 238.0794; found 239.4 $[M + H]^+$.

1-[4-(2,4,6-Trichloro-phenylethynyl)-phenyl]ethanone

Mixture of the product and 2,4,6,2′,4′,6′-Hexachloro-biphenyl, yellow crystal. ^{1}H NMR (acetone-d_6) δ 2.63 (s, 3H, CH_3), 7.68 (s, 2H, CH), 7.76 (d, J = 8.4 Hz, 2H, CH), 8.07 (d, J = 8.4 Hz, 2H, CH). GC/TOF HRMS-EI: calcd for $C_{16}H_9Cl_3O$, 321.9719; found 321.9717.

5-(4-Fluoro-phenylethynyl)-thiophene-2-carbaldehyde

Yellow crystals; m.p.: 98–99 °C. ^{1}H NMR ($CDCl_3$) δ 7.08 (t, J = 8.4 Hz, 2H, CH), 7.10 (d, J = 4 Hz, 1H, CH), 7.53 (t, J = 8 Hz, 2H, CH), 7.68 (d, J = 4 Hz, 1H, CH), 9.87 (s, 1H, CHO). ^{13}C NMR ($CDCl_3$) δ 87.65 (C≡C), 96.7 (C≡C), 115.8 (aromatic C), 116.1 (aromatic C), 132.5 (aromatic C), 132.7 (aromatic C), 133.7 (aromatic C), 133.8 (aromatic C), 135.9 (aromatic C), 143.9 (aromatic C), 161.8 (aromatic C), 164.4 (aromatic C), 182.3 (CHO). GC-MS: calcd for $C_{13}H_7FOS$, 230.0202; found 230.

X-ray Crystal Structure Determination of Pyrrole 5

The crystal suitable for the X-ray diffraction study was prepared by slow crystallization of an ether solution of **5**. Diffraction data for **5** were collected on a Siemens Smart CCD diffractometer equipped with graphite monochromated Mo K_α radiation (λ = 0.71073 Å) at 293 K. The structure was solved by direct methods (SHELXS-97[21]) and subsequent difference Fourier syntheses, and refined by a full-matrix least-squares on (F^2) using the SHELXL-97 programme[21]. Nonhydrogen atoms were refined with anisotropic displacement parameters and hydrogen atoms were included in the riding model approximation.

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Supporting information

Supporting information may be found in the online version of this article.

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