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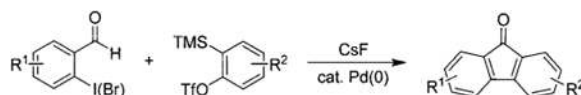
Efficient Synthesis of Fluoren-9-ones by the Palladium-Catalyzed Annulation of Arynes by 2-Haloarenecarboxaldehydes

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Abstract



Fluoren-9-ones and derivatives are readily prepared in good yields by the annulation of in situ generated arynes by 2-haloarenecarboxaldehydes in the presence of a palladium catalyst.

Introduction

Recent groundbreaking work in the area of metal-catalyzed transformations of arynes, including the palladium-catalyzed cyclotrimerization of benzyne to form triphenylenes,¹ has provided novel new ways to rapidly construct fused aromatic polycycles. The metal-catalyzed cocyclization of arynes with alkynes has also been investigated.² In addition, metal-catalyzed carbonylative cycloadditions of arynes³ and the cocyclotrimerization of arynes with bicyclic alkenes⁴ and allenes⁵ have been reported. More recently, our group and others have synthesized fused polycyclic aromatics by palladium-catalyzed annulations of arynes with aryl halides.⁶ We have also reported a palladium-catalyzed, three-component, sequential intermolecular coupling of aryl halides, alkynes, and arynes.⁷

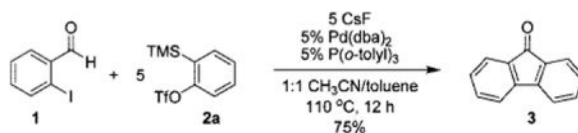
The construction of heterocycles and carbocycles by the palladium-catalyzed annulation of alkynes by functionally substituted aryl halides has proven a powerful synthetic tool.⁸ Specifically, we have reported that 2-halobenzaldehydes can react with internal alkynes in the presence of a palladium catalyst to form substituted indenones in good yields.⁹ Analogous to that work, we recently reported the synthesis of fluoren-9-ones by the palladium-catalyzed annulation of in situ generated benzyne by 2-haloarenecarboxaldehydes.¹⁰ This provides a convenient synthesis of fluoren-9-ones, which are an important class of carbocycle, because of their important role in pharmaceutical applications,¹¹ as photosensitizers,¹² and their use as key intermediates in organic synthesis.¹³ A number of fluoren-9-one natural products, including dengibsin, dengibsinin, and dendroflorin, have recently been reported to occur in the Asiatic orchid *Dendrobium gibsonii* Lindley (Figure 1).¹⁴ We now report the full details of our work on the palladium-catalyzed annulation of arynes by 2-haloarenecarboxaldehydes.

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Supporting Information Available: General experimental procedures and spectral data for all previously unreported starting materials and products. This material is available free of charge via the Internet at <http://pubs.acs.org>.

Results and Discussion

In our earlier study, it was found that the “optimal” conditions for our palladium-catalyzed annulation of arynes by 2-haloarenecarboxaldehydes involves stirring 0.3 mmol of the 2-iodobenzaldehyde (**1**), 1.5 mmol of the benzyne precursor 2-(trimethylsilyl)phenyl triflate (**2a**), 1.5 mmol of CsF, 5 mol % of Pd(dba)₂, and 5 mol % of P(*o*-tolyl)₃ ligand in 4 mL of 1:1 MeCN/toluene at 110 °C for 12 h. This affords the desired fluoren-9-one (**3**) in a 75% yield (eq 1).

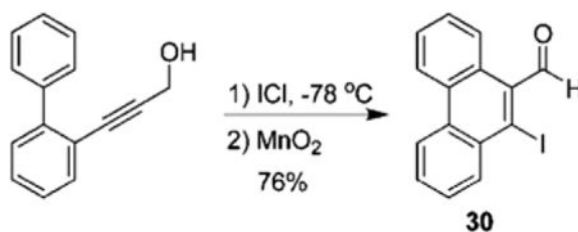


(1)

To determine the scope and limitations of this chemistry, a number of new *o*-haloarenecarboxaldehydes were required. However, many of the necessary starting materials were not readily accessible from commercial sources. The synthesis of *o*-iodonaphthalenecarboxaldehyde starting materials was achieved by employing a useful variant of some of our previously reported¹⁵ iodocyclization chemistry using appropriate benzylic-substituted propargylic diols, followed by oxidation of the resulting naphthalen-1-ylmethanols by MnO₂ (scheme 1). The requisite diols are easily prepared by the reaction of the lithium acetylide dianion of propargyl alcohol with the corresponding 2-arylacetaldehyde or 2-arylacetone in THF at 0 °C, followed by quenching with a saturated solution of aqueous NH₄Cl.

In addition to the *o*-halonaphthalenecarboxaldehydes described above, we prepared 6-iodobenzothiophene-7-carboxaldehyde (**28**) by an analogous route starting from 2-(thiophen-3-yl)acetaldehyde (scheme 2). The iodocyclization of the thiophene-containing diol occurred selectively at the 2-position of the thiophene. The major side product appeared to arise by simple dehydration to an enynol product that did not cyclize.

The synthesis of 10-iodophenanthrene-9-carbaldehyde (**30**) was achieved by the iodocyclization of 3-(biphen-2-yl)prop-2-yn-1-ol, followed by oxidation with MnO₂ (eq 2).¹⁶



(2)

With a number of new *o*-iodoarenecarboxaldehydes in hand, we examined the scope of the fluoren-9-one synthesis (Table 1). When 2-iodobenzaldehyde (**1**) and 2-bromobenzaldehyde (**4**) were allowed to react with 2-(trimethylsilyl)phenyl trifluoromethanesulfonate (**2a**) under

our optimized conditions, fluoren-9-one (**3**) was isolated in good yields, although a 2-fold increase in reaction time was required for the reaction of **4** to reach completion (Table 1, compare entries 1 and 2). 5-Bromo-2-iodobenzaldehyde (**5**) reacted selectively to afford the desired 2-bromofluoren-9-one (**6**) in good yield (Table 1, entry 3). 6-Fluoro-2-iodobenzaldehyde (**7**) reacted cleanly to provide 1-fluorofluoren-9-one (**8**) in an 82% yield (Table 1, entry 4). The slight increase in the yield of **8** compared to the parent system may be due to the electron-withdrawing nature of the fluorine atom on the aromatic ring, which presumably facilitates the oxidative addition of Pd(0) to the carbon–iodine bond of **7**. In addition, the fluorine atom may increase the electrophilicity of the aldehyde moiety, promoting the final cyclization step (see the later mechanistic discussion). On the contrary, the reaction of 2-iodo-4,5-methylenedioxybenzaldehyde (**9**) with triflate **2a** provided only a 50% yield of the desired fluoren-9-one **10** (Table 1, entry 5). This marked decrease in yield, as compared to the parent system, may be due to the electron-rich aromatic ring. Both 2-iodo-5,6-methylenedioxybenzaldehyde (**11**) and 2-bromo-5,6-methylenedioxybenzaldehyde (**13**) provided the corresponding fluoren-9-one **12**. However, the aryl bromide gave a significantly reduced yield (Table 1, compare entries 6 and 7). The higher yield of **12** from **11**, as opposed to that of **10** from **9**, might be explained by the electron-withdrawing inductive effect of the oxygen atoms of **11** being greater due to their proximity to the aldehyde group, thus making the aldehyde more electrophilic (Table 1, compare entries 5 and 6). When 2-iodo-4,5-dimethoxybenzaldehyde (**14**) was reacted with triflate **2**, the desired fluoren-9-one **15** obtained in a 53% yield (Table 1, entry 8). This result is in line with the reaction of triflate **2a** with aldehyde **9**. 2-Iodo-3,4,5-trimethoxybenzaldehyde (**16**) provided 2,3,4-trimethoxyfluoren-9-one (**17**) in only a modest yield of 41% (Table 1, entry 9). The decrease in yield, compared with other aryl ethers, is presumably due to a steric effect of the MeO group ortho to the iodine atom. Steric congestion around the carbon–iodine bond may hinder oxidative addition of palladium to the C–I bond.

In addition to benzaldehyde substrates, the annulation reaction has also been applied to 2-iodonaphthalene-1-carboxaldehydes. The annulation of triflate **2a** by 1-iodonaphthalene-2-carboxaldehyde (**18**) provided fluorenone derivative **19** in a 48% yield (Table 1, entry 10). A marked increase in the yield of fluorenone was observed when 2-iodonaphthalene-1-carboxaldehyde (**20**) was allowed to react with triflate **2a** (Table 1, compare entries 10 and 11). The increase in yield of **21**, compared to regioisomer **19**, is apparently due to decreased steric crowding around the carbon–iodine bond, resulting in a more facile oxidative addition of the palladium moiety. Reactions of 2-iodo-4-methylnaphthalene-1-carboxaldehyde (**22**) and 2-iodo-4-phenylnaphthalene-1-carboxaldehyde (**24**) with triflate **2a** proceeded smoothly and provided the corresponding fluorenones **23** and **25**, respectively, in good yields (Table 1, entries 12 and 13). 2-Iodo-3,7-dimethylnaphthalene-1-carboxaldehyde (**26**) afforded the desired compound **27** (Table 1, entry 14). However, the yield suffered, presumably due to steric hindrance in the vicinity of the carbon–iodine bond of **26**. 6-Iodobenzothiophene-7-carboxaldehyde (**28**) gave the corresponding thiophene-containing fluorenone **29** in a 52% yield (Table 1, entry 15). When phenanthrene **30** was allowed to react with triflate **2a**, the desired fluoren-9-one derivative **31** was obtained in a 61% yield (Table 1, entry 16). Naphthalene **32** was employed to see if this methodology could be extended to 6-membered rings, but unfortunately, triphenylene was observed as the major product of this reaction, along with the reduced starting material naphthalene-1-carboxaldehyde (Table 1, entry 17). A double annulation was attempted by using diiododialdehyde **33**. Unfortunately, the latter reaction provided a complex reaction mixture, and none of the desired product was observed (Table 1, entry 18). A similar result was obtained when the reaction was performed using 0.3 mmol of diiododialdehyde **33**, 3.0 mmol of 2-(trimethylsilyl)phenyl triflate (**2a**), 3.0 mmol of CsF, 10 mol % of Pd(dba)₂, and 10 mol % of P(*o*-tolyl)₃ ligand in 8 mL of 1:1 CH₃CN/toluene.

In addition to the above reactions, which examined only the use of the benzyne precursor triflate **2a** as an annulation partner, other aryne precursors have been examined in our methodology. 4,5-Dimethoxybenzyne precursor **2b** was examined under our annulation conditions and gave the expected 2,3-dimethoxyfluoren-9-one (**15**), although the yield was poor (Table 1, entry 19). The low yield in this latter reaction may be attributed to the slower rate of generation of 4,5-dimethoxybenzyne from **2b**, compared with the generation of benzyne from **2a**, as has been suggested by earlier work in our group.^{6a,c} However, when dimethylbenzyne precursor **2c** was allowed to react with 2-iodobenzaldehydes **1** and **7** under our optimized conditions, it provided the corresponding fluoren-9-one products **34** and **35**, respectively, in good yields (Table 1, entries 20 and 21). The reaction of 3-methoxybenzyne, generated from triflate **2d**, exhibited good regioselectivity (Table 1, entry 22). The reaction gave rise to both isomeric methoxyfluoren-9-ones in approximately a 9:1 ratio as determined by gas chromatographic analysis. 1-Methoxyfluoren-9-one (**36**) was the major product as determined by comparison of its ¹H and ¹³C NMR spectra with those of the known compound.¹⁷ The preference for regioisomer **36** over the other regioisomer can be attributed to coordination of the methoxy group to the palladium in the biaryl palladium intermediate **37** (Figure 2.).¹⁸ This regiochemistry also places the palladium on the inductively more thermodynamically stable carbanionic carbon. Intermediate **37** is also the product one would expect from the aryl moiety of the initial ArPdX adding to the most sterically accessible carbon of the aryne. As observed in the carbopalladation of alkynes,⁸ Pd presumably prefers to add to the more hindered end of the aryne, which is ortho to the methoxy group.

In addition to benzyne precursors, we have also examined the effect of naphthyne^{2c} precursor **2e** on the annulation process. We were pleased to find that one major regioisomer was formed in a 50% yield from the reaction of naphthyne precursor **2e** with aldehyde **1** (Table 1, entry 23). This result is in agreement with the suggestion that the aryl moiety of the initial ArPdX adds to the more sterically exposed carbon of the aryne and that Pd prefers to add to the more hindered C1 of naphthyne.

In addition to the substrates illustrated in Table 1, we have also attempted to employ substituted 2-haloacrylaldehydes in this palladium-catalyzed annulation reaction to synthesize indenones.⁹ Unfortunately, reactions with 2-iodocyclohex-1-enecarboxaldehyde and (*Z*)-3-iodo-3-phenylacrylaldehyde produced complex mixtures, and only poor yields of indenones were achieved. Also, our attempts employing pyridine substrates, such as 2-bromopyridine-3-carboxaldehyde, 4-bromopyridine-3-carboxaldehyde, and 2-fluoro-4-iodopyridine-3-carboxaldehyde, as starting materials did not lead to any formation of the desired fluoren-9-ones. This result is not surprising, since pyridine itself is known to react with benzyne to give novel polymers with *o*-phenylene and 2,3-dihydropyridine units in the main chain.¹⁹

Based on previously reported palladium-catalyzed annulations of alkynes,⁸ particularly the synthesis of indenones by the palladium-catalyzed coupling of internal alkynes with 2-haloarene carboxaldehydes,⁹ we propose that this fluorenone synthesis proceeds through one or more of several possible pathways shown in scheme 3. One possible pathway proceeds by the oxidative cyclization of Pd(0) with aryne **A** generated from the silyl triflate to form palladacycle **B** (path a).²⁰ Oxidative addition of **1** to this palladacycle forms Pd(IV) intermediate **C**. Reductive elimination gives rise to arylpalladium(II) intermediate **E**. However, we cannot rule out the possibility that Pd(0) inserts directly into the C–I bond of **1** to form intermediate **D**, which then undergoes carbopalladation of the aryne **A** to give rise to intermediate **E** (path b). This pathway has been suggested by experiments in our earlier work on the synthesis of fused polycyclic aromatics by the palladium-catalyzed annulation of arynes by aryl halides.^{6a,c} Arylpalladium intermediate **E** can then add the carbon–palladium bond across the aldehyde to produce a palladium(II) alkoxide **F**,²¹ which can

undergo β -hydride elimination to produce the fluorenone product (path d). Alternatively, intermediate **E** can undergo oxidative addition of the aldehyde C–H bond to form palladium(IV) intermediate **G**,²² followed by elimination of HI, and regeneration of the Pd(0) catalyst by further reductive elimination to the fluoren-9-one (path c). A similar mechanism involving oxidative addition of the aldehyde to an organopalladium(II) intermediate has been proposed for the palladium-catalyzed reactions of *o*-bromobenzaldehyde with methyl acrylate.²³ However, there does not appear to be any particular precedent favoring any of these pathways.

In order to demonstrate the utility of 2-bromofluoren-9-one (**6**) generated by our methodology, we have elaborated the carbon–bromine bond by palladium-catalyzed, microwave-assisted Sonogashira²⁴ and Suzuki–Miyaura²⁵ cross-coupling reactions (scheme 4). These reactions proceeded cleanly to give acetylenic fluoren-9-one **39** and 2-(3,4,5-trimethoxyphenyl)fluoren-9-one (**38**) in high yields.

Conclusions

In summary, we have developed a novel synthesis of fluoren-9-ones, which involves the palladium-catalyzed annulation reaction of arynes by 2-haloarene-carboxaldehydes. This method provides an efficient synthesis of substituted fluoren-9-ones from readily available starting materials. In addition, this methodology provides a route to fluoren-9-ones that avoids the use of harsh oxidizing agents and strong mineral acids.²⁶ Our process has been shown to be tolerant of benzaldehydes containing multiple halogens. The resulting halogenated 2-bromofluoren-9-one may be further elaborated by palladium-catalyzed processes, such as Sonogashira and Suzuki–Miyaura cross-coupling reactions. Furthermore, this methodology has been extended to naphthalene derivatives of fluoren-9-ones and has also been shown to work in the presence of a heterocycle.

Experimental Section

General Procedure for the Synthesis of Alkynediols

Propargyl alcohol (16.6 mmol, 930 mg, 0.98 mL) was dissolved in THF (100 mL) and cooled to 0 °C. Under an atmosphere of argon, *n*-BuLi (2.5 M in hexanes, 33.2 mmol, 13.3 mL) was added slowly and the resulting solution allowed to stir at 0 °C for 1 h. A solution of the appropriate arylacetaldehyde or arylacetone (8.3 mmol) in THF (10 mL) was added slowly, and the solution was allowed to warm to room temperature over a period of 12 h. The solution was quenched with a satd aq NH₄Cl solution and extracted with EtOAc (3 × 20 mL). The organic layers were combined, dried (MgSO₄), and concentrated under reduced pressure. The crude products were isolated by flash column chromatography on silica gel (2:1 hexanes/EtOAc).

5-Phenylpent-2-yne-1,4-diol

The indicated compound was isolated as a pale yellow oil: ¹H NMR (CDCl₃, 400 MHz) δ 2.94–2.95 (d, *J* = 6.6 Hz, 2H), 3.66 (br s, 2H), 4.16 (s, 2H), 4.52–4.55 (t, *J* = 6.5 Hz, 1H), 7.21–7.30 (m, 5H); ¹³C NMR (CDCl₃) δ 44.0, 50.7, 63.2, 84.0, 86.1, 127.0, 128.5, 129.8, 136.8; HRMS calcd for C₁₁H₁₂O₂ 176.0837, found 176.0840.

General Procedure for the Electrophilic Cyclization of Alkynediols by ICl, Followed by Oxidation with MnO₂

A 1.2 mmol portion of the alkynediol, 2 equiv of NaHCO₃, and 8 mL of CH₃CN were placed in a vial and stirred for 1 min at room temperature. Two equivalents of ICl in 2 mL of CH₃CN was added dropwise to the vial. The reaction mixture was stirred at room

temperature for 10 min. The reaction mixture was then diluted with 25 mL of EtOAc and washed with 20 mL of satd aq Na₂S₂O₃. The organic layer was separated, and the aqueous layer was extracted with another 25 mL of EtOAc. The combined organic layers were dried over MgSO₄ and filtered. The solvent was evaporated under reduced pressure and the crude residue was filtered through a plug of silica gel rinsed with 25% EtOAc in hexanes. The solvent was evaporated under reduced pressure and the residue was dissolved in CHCl₃ (50 mL). The solution was cooled to 0 °C and MnO₂ (6.0 equiv based on the alkynediol) was added. The solution was warmed to room temperature and stirred for 18 h. The suspension was filtered through a plug of celite and the solvent evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel using a gradient solvent system (40:1 hexanes/EtOAc to 9:1 hexanes/EtOAc).

2-Iodonaphthalene-1-carboxaldehyde (20)

The indicated compound was isolated as a yellow solid: mp 77–79 °C; ¹H NMR (CDCl₃, 400 MHz) δ 7.55–7.59 (dt, *J* = 1.1, 7.5 Hz, 1H), 7.62–7.67 (m, 2H), 7.80–7.82 (d, *J* = 8.1 Hz, 1H), 7.94–7.96 (d, *J* = 8.7 Hz, 1H), 9.01–9.03 (d, *J* = 8.7 Hz, 1H), 10.39 (s, 1H); ¹³C NMR (CDCl₃) δ 105.6, 124.2, 127.5, 128.5, 129.4, 130.6, 131.7, 133.8, 135.1, 137.1, 199.0; HRMS calcd for C₁₁H₇IO 281.9542, found 281.9546.

Procedure for the Cyclization of 3-(Biphenyl-2-yl)prop-2-yn-1-ol by ICl and Oxidation by MnO₂ To Form 10-Iodophenanthrene-9-carbaldehyde (30)

To a solution of 3-(biphenyl-2-yl)prop-2-yn-1-ol (0.96 mmol) in CH₂Cl₂ (10 mL) under N₂ was added ICl (1.2 equiv) in CH₂Cl₂ (2 mL) at –78 °C. The reaction mixture was stirred at –78 °C for 0.5 h. The reaction mixture was then diluted with 25 mL of EtOAc and washed with 20 mL of satd aq Na₂S₂O₃. The organic layer was separated, and the aqueous layer was extracted with another 25 mL of EtOAc. The combined organic layers were dried over MgSO₄ and filtered. The solvent was evaporated under reduced pressure, and the crude residue was filtered through a plug of silica gel and rinsed with 25% EtOAc in hexanes. The solvent was evaporated under reduced pressure, and the residue was dissolved in CHCl₃ (50 mL). The solution was cooled to 0 °C, and MnO₂ (6.0 equiv) was added. The solution was warmed to room temperature and stirred for 18 h. The suspension was filtered through a plug of Celite and the solvent evaporated under reduced pressure. The residue was purified by column chromatography on silica gel using a gradient solvent system (40:1 hexanes/EtOAc to 9:1 hexanes/EtOAc) to afford 243 mg (76%) of the product as a yellow oil that solidified upon standing: mp 80–82 °C; ¹H NMR (CDCl₃, 400 MHz) δ 7.34–7.41 (m, 5H), 7.43–7.47 (m, 2H), 7.50–7.54 (dt, *J* = 1.5, 7.5 Hz, 1H), 9.26 (s, 1H); ¹³C NMR (CDCl₃) δ 106.5, 127.8, 128.1, 128.6, 128.8, 128.9, 130.7, 130.8, 139.6, 140.2, 150.4, 185.9; HRMS calcd for C₁₅H₉IO 331.9698, found 331.9700.

General Procedure for the Palladium-Catalyzed Synthesis of Fluoren-9-ones

The 2-iodoarene-carboxaldehyde (0.30 mmol), the 2-(trimethylsilyl)aryl triflate (1.50 mmol), CsF (1.50 mmol), Pd(dba)₂ (0.015 mmol), P(*o*-tolyl)₃ (0.015 mmol), 2 mL of toluene, and 2 mL of MeCN were placed in a 4 dram vial, and the vial was sealed. The reaction mixture was stirred first at room temperature for 1 min and then heated to 110 °C for 12 h. The mixture was allowed to cool to room temperature (CAUTION: OPENING THE VIAL AT HIGH TEMPERATURE CAN BE DANGEROUS!), diluted with diethyl ether, washed with brine, dried over anhydrous MgSO₄, and concentrated under reduced pressure. The product was isolated by flash chromatography on silica gel using hexanes/EtOAc as the eluent.

1-Fluoro-9H-fluoren-9-one (8)

The indicated compound was obtained as a yellow solid in an 82% yield: mp 117–119 °C; ¹H NMR (CDCl₃, 300 MHz) δ 6.89–6.95 (t, *J* 8.4 Hz, 1H), 7.29–7.35 (m, 2H), 7.43–7.53 (m, 3H), 7.65–7.67 (d, *J* = 7.5 Hz, 1H); ¹³C NMR (CDCl₃) δ 16.61, 116.65, 117.59, 117.87, 120.12, 120.29, 120.88, 124.69, 129.90, 134.19, 134.86, 137.23, 137.34, 143.59, 143.63, 146.56, 146.61, 157.79, 161.29, 190.36 (extra peaks due to F splitting); HRMS calcd for C₁₃H₇FO 198.0481, found 198.0485.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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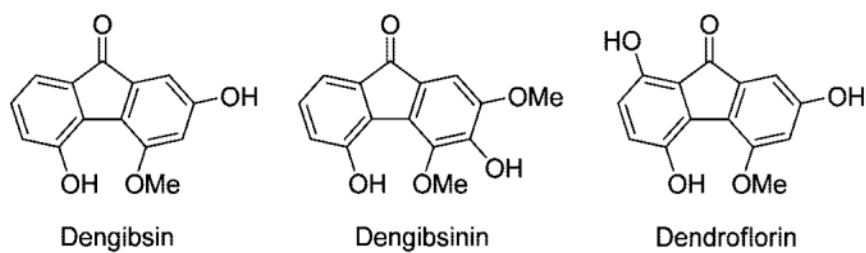


Figure 1.

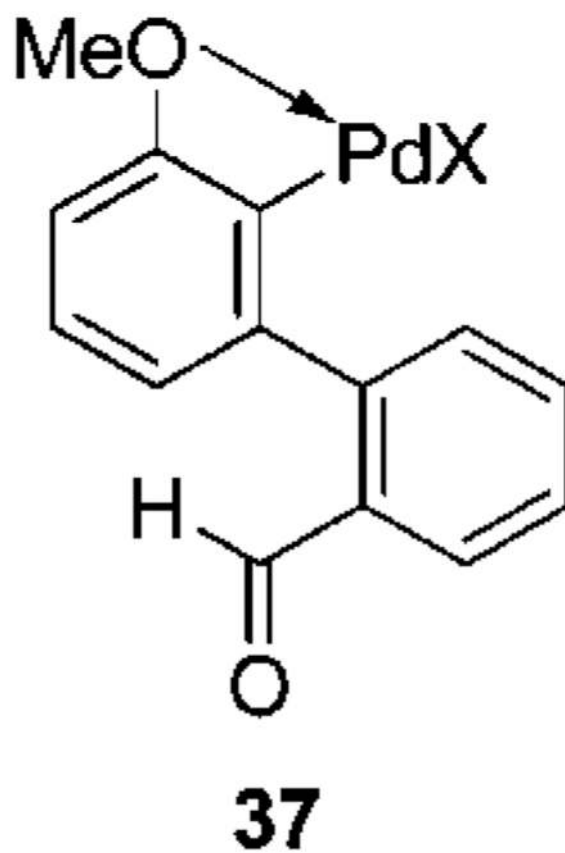
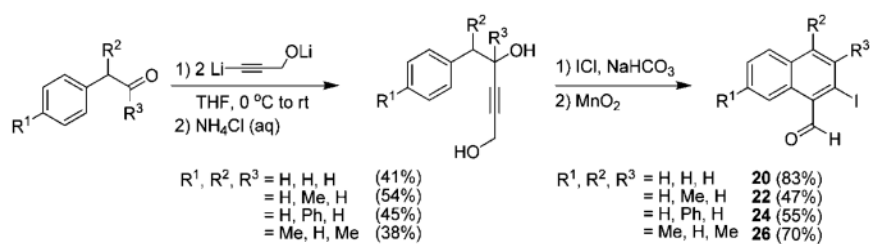
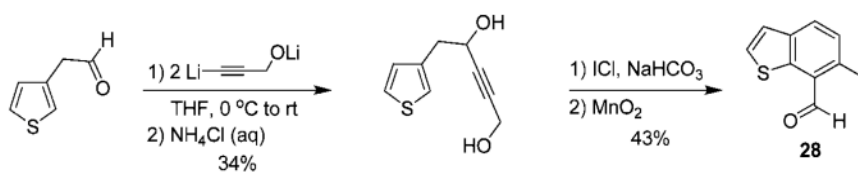


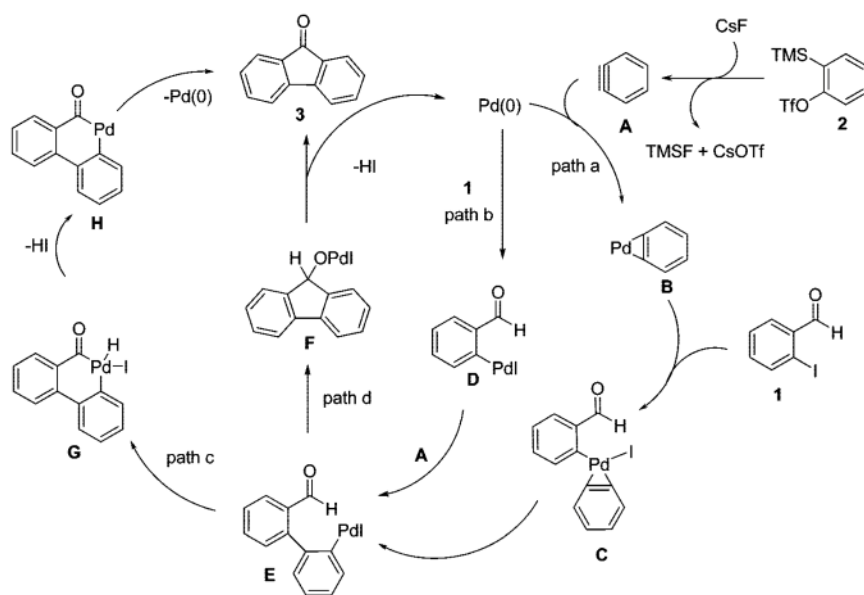
Figure 2.



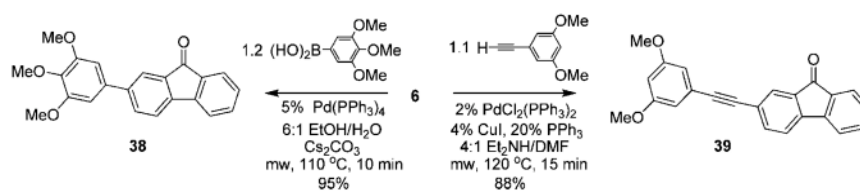
Scheme 1.



Scheme 2.



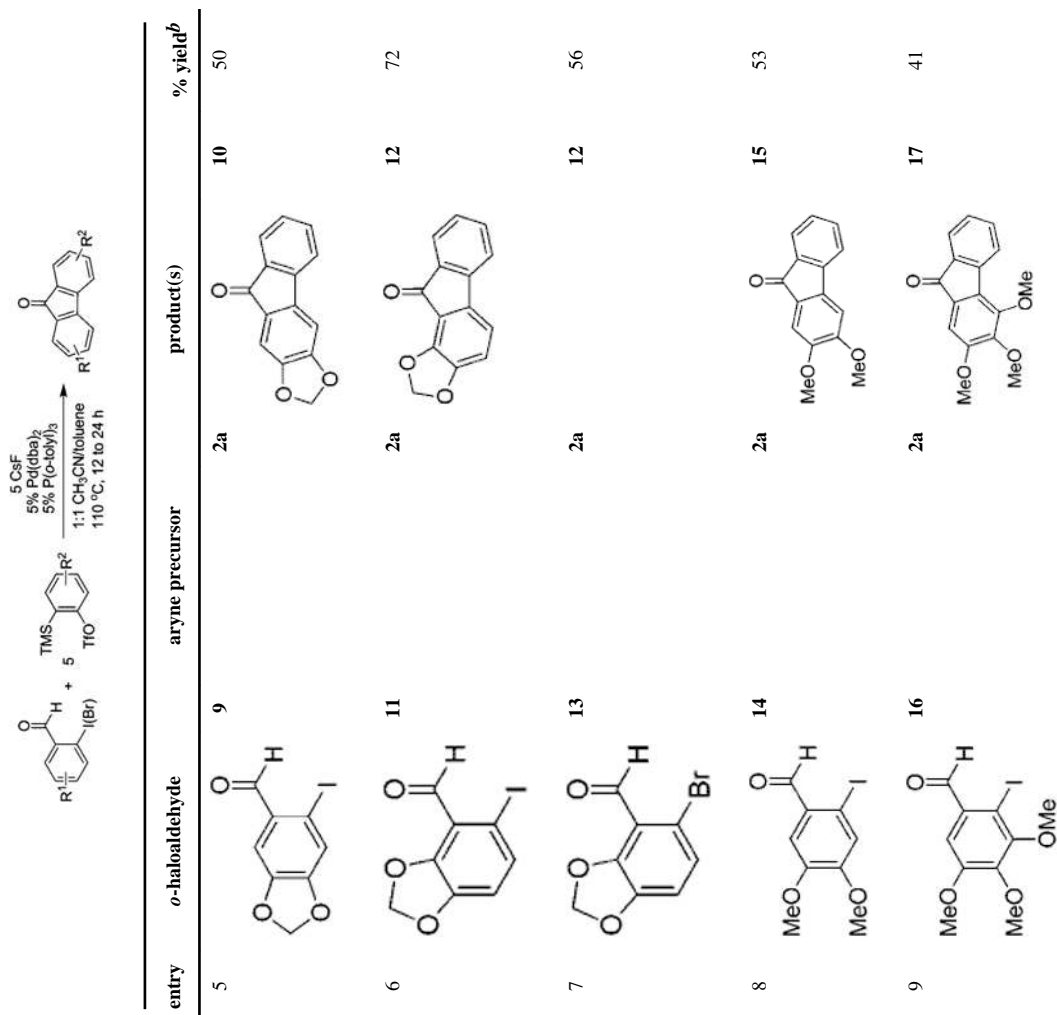
Scheme 3.

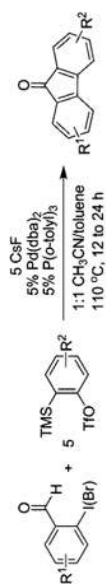


Scheme 4.

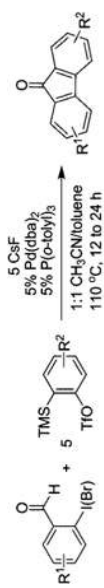
Table 1
Synthesis of Fluoren-9-ones by the Palladium-Catalyzed Annulation of Arynes by *o*-Haloarenealdehydes^a

entry	<i>o</i> -haloaldehyde	aryne precursor	product(s)	% yield ^b
1				75
2				73 ^c
3				61
4				82

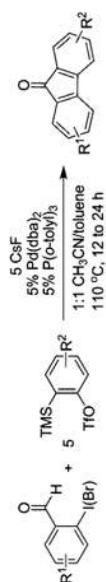




entry	<i>o</i> -haloaldehyde	aryne precursor	product(s)	% yield ^b
10				48
11				59
12				61
13				78



entry	<i>o</i> -haloaldehyde	aryne precursor	product(s)	% yield ^b
14		26	 2a	48
15		28	 2a	52
16		30	 2a	61
17		32	2a	0



entry	<i>o</i> -haloaldehyde	aryne precursor	product(s)	% yield ^b
18				messy
19				33 ^d
20				71
21				73
22				61 ^e
23				trace 50

^aUnless otherwise specified, all reactions were carried out using 0.3 mmol of the aldehyde, 1.5 mmol of the aryne precursor, 1.5 mmol of CsF, 5 mol % of Pd(dba)₂, and 5 mol % of P (o-tol)₃ in 4 mL of 1:1 CH₃CN/toluene at 110 °C for 12 h.

^bIsolated yield after column chromatography on silica gel.

^cThe reaction required 24 h to reach completion and the yield was determined by GC-MS.

^dThe yield was determined by ¹H NMR spectroscopy.

^eThe yield of the other isomer was 7% according to gas chromatographic analysis.