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Synthesis of Fluorenes *via* the Palladium-Catalyzed 5-*exo*-*dig* Annulation of *o*-Alkynylbiaryls

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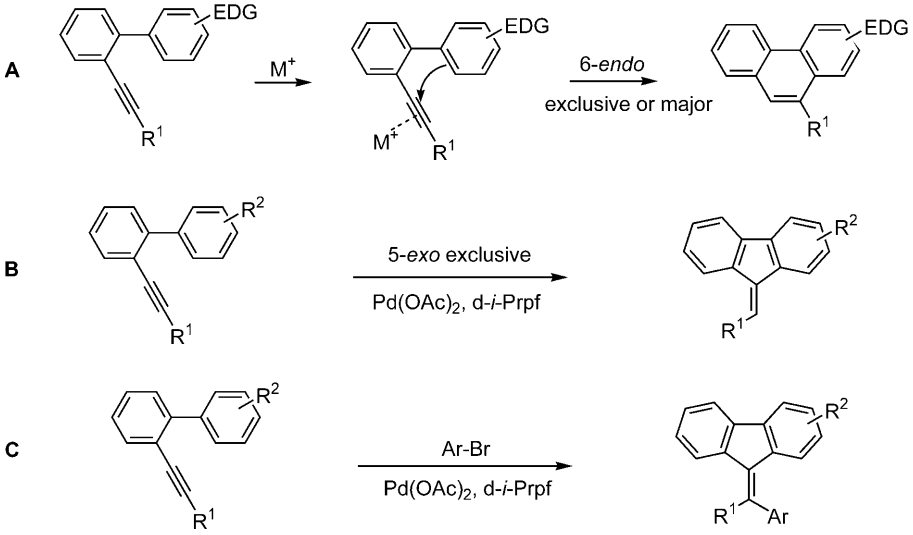
Dedicated to Prof. Armin de Meijere on the occasion of his 70th birthday.

Abstract: The direct palladium-catalyzed intramolecular hydroarylation of *o*-alkynylbiaryls proceeded in a highly stereoselective manner producing fluorenes **2**, the products of 5-*exo*-*dig* cyclization, in excellent yields. The cascade intermolecular arylation, incorporated in this transformation, allowed for the efficient synthesis of fully substituted fluorenes **12**. These cyclizations proceed more rapidly with electron-deficient benzene rings which, in combination with a substantial isotope effect observed, strongly supports a C–H activation mechanism for the key annulation step.

Keywords: alkynes; annulations; arylation; C–H activation; palladium

Introduction

Palladium-catalyzed annulation reactions serve as a powerful tool for the construction of fused polycyclic aromatic and heteroaromatic compounds.[1] Activation of the C≡C triple bond by π-philic metals, followed by cyclization with the adjacent aromatic ring, proved efficient for construction of fused five- and six-membered ring systems.[2] One of the representative examples of this approach is the intramolecular hydroarylation of alkynylbiaryls. The palladium-catalyzed version of it was first reported by Fujiwara.[3] The other transition metal-[4,5] and Lewis acid-catalyzed[6] versions of this reaction quickly emerged shortly after. Generally, this reaction proceeds *via* the Friedel–Crafts-type electrophilic aromatic substitution pathway and is most efficient with electron-rich aromatic rings. Thus, as reported by Fürstner, *o*-alkynylbiaryls possessing an electron-rich aryl ring in the presence of transition metals undergo a facile intra-



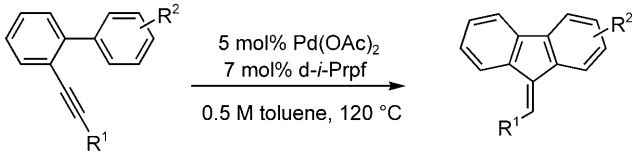
Scheme 1.

molecular hydroarylation reaction leading to the exclusive or predominant formation of the phenanthrene frameworks *via* a 6-*endo*-*dig* carbocyclization pathway (Scheme 1, **A**). In contrast, we have recently found that employment of the neutral $Pd(OAc)_2$/d-*i*-Prpf catalytic system triggered the exclusive 5-*endo*-*dig* cyclization leading to the fluorene derivatives (Scheme 1, **B**). We have shown that this reaction is most efficient with electron-neutral and electron-poor arenes.[7] In this paper, we discuss the previously communicated intramolecular hydroarylation of *o*-alkynylbiaryls in more detail, as well as the extension of this methodology to the cascade arylation of *o*-alkynylbiaryls with aryl halides, followed by cyclization into the polysubstituted fluorenes (Scheme 1, **C**).

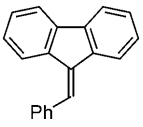
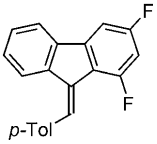
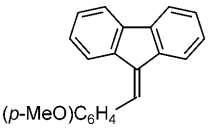
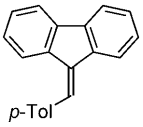
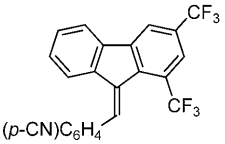
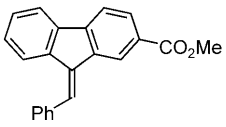
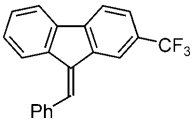
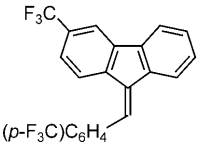
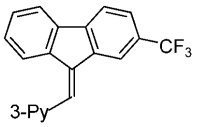
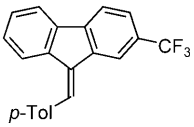
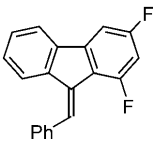
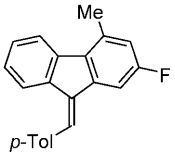
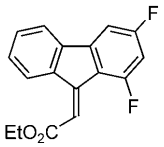
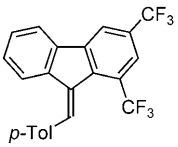
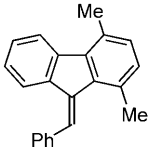
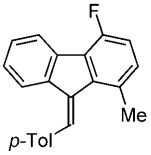
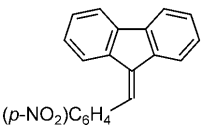
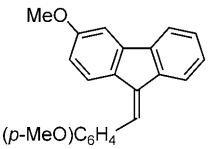
Results and Discussion

We were intrigued by the palladium-catalyzed intramolecular hydroarylation of alkynylbiaryls that proceeds under ligand-free acidic conditions and produced predominantly 6-*exo*-*dig* cyclization products. Initially, it was believed that this reaction proceeds

Table 1. Pd-catalyzed hydroarylation of *o*-alkynylbiaryls.[a]



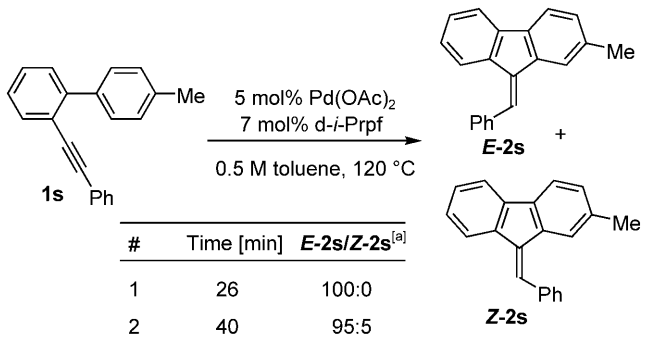
1 **2**

#	Product	Time [h]/ Yield [%][b]	#	Product	Time [h]/ Yield [%][b]	#	Product	Time [h]/ Yield [%][b]
1	**2a** 	2.5/98	7	**2g** 	4.0/95	13	**2m** 	5.0/87
2	**2b** 	3.0/95	8	**2h** 	1.0/93	14	**2n** 	1.0/85
3	**2c** 	1.5/96	9	**2i** 	0.5/98	15	**2o** 	1.5/77
4	**2d** 	2.0/96	10	**2j** 	3.0/93	16	**2p** 	24/47
5	**2e** 	0.5/79	11	**2k** 	3.0/94	17	**2q** 	48/30
6	**2f** 	3.0/92	12	**2l** 	4.0/89	18	**2r** 	6.0/86

[a] *Reaction conditions:* 0.5 mmol of **1**, 0.025 mmol of $Pd(OAc)_2$, 0.035 mmol of d-*i*-Prpf, 1 mL of toluene, 120 °C.
[b] Isolated yields.

via a C–H activation path.[3] However, recently an electrophilic substitution path for the key annulation step of this transformation was unambiguously established.[8] We hypothesized that switching from acidic to neutral catalytic conditions may affect the mechanism of this reaction. Accordingly, the cyclization of *o*-alkynylbiaryl **1** under the acid-free conditions has been investigated. It was found that biaryl **1a** in the presence of catalytic amounts of $Pd(OAc)_2$/dppf in toluene at 120 °C underwent a facile *5-exo-dig* cyclization to produce the fluorene **2a** in 70% yield. Switching to a bulkier 1,1′-bis(diisopropylphosphino)ferrocene (d-*i*-Prpf) led to even more efficient cyclization producing fluorene **2a** virtually quantitatively (Table 1, entry 1).

With these conditions in hand, we explored the generality of this transformation. Thus, a variety of *o*-alkynylbiaryls possessing electron-neutral and, most surprisingly, electron-deficient aryl rings underwent smooth *5-exo-dig* carbocyclization to produce fluorenes **2a–j** in good to excellent yields (Table 1). It was found that a variety of substituents, such as F (entries, 5, 6, 7, 10, 16), NO_2 (entry 12) CO_2Me (entries 5 and 14) and CN (entry 8) were perfectly tolerated under these reaction conditions. It is worth mentioning that, in contrast to the reported intramolecular hydroarylations of alkynes,[3–6,8] *o*-alkynylbiaryls possessing electron-deficient substituents (R^2 = F, CF_3, CO_2Me) underwent the carbocyclization reaction faster compared to the biaryls bearing electron-neutral aryl rings. Although no substituent effect at the alkyne moiety (R^1) on the reaction yield was observed, biaryls bearing electron-defficient alkynes reacted slightly faster than their non-activated analogues (entries 5, 8, 9, and 12). Most importantly, all cyclization reactions of **1a–r** proceeded with high *cis*-stereoselectivity, producing fluorenes **2a–r** as single geometrical isomers.[9] It was found that, contrary to the previous reports on hydroarylations under acidic conditions,[3–6,8] cyclizations of biaryls containing electron-donating groups in the presence of $Pd(OAc)_2$/d-*i*-Prpf proceeded substantially slower. Thus, the cyclization of *o*-alkynylbiaryl **1q**, possessing methyl groups at the adjacent aromatic ring, was extremely slow, producing fluorene **2q** after 48 h in 30% yield only (Table 1, entry 17). Likewise, annulation of tolyl-substituted alkynylbiaryl **1s** proceeded quite sluggishly. Initially, *E*-**2s**, the "normal" stereoisomer of hydroarylation, was produced in trace amounts. However, towards completion of the reaction (20 h), increased amounts of *Z*-**2s** were produced, suggesting that *E*/*Z*-isomerization under the prolong heating (Scheme 2).[10]

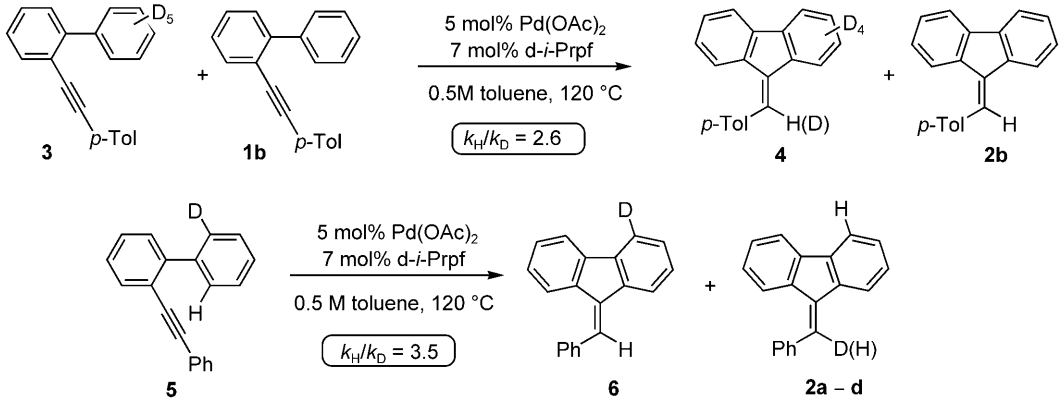


#	Time [min]	*E*-2s/*Z*-2s[a]
1	26	100:0
2	40	95:5
3	60	87:13
4	480	82:18
5	720	67:33

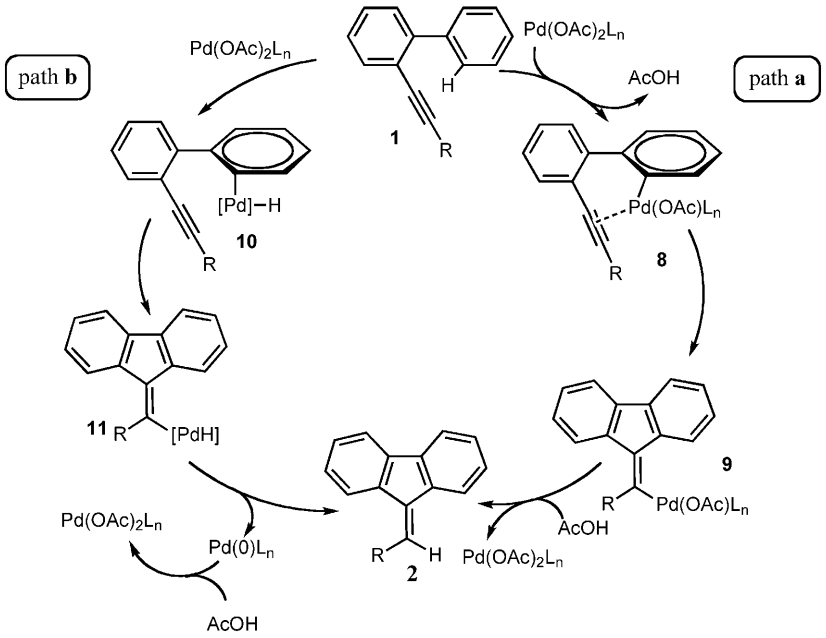
[a] Determined by GC/MS.

Scheme 2.

Towards a better understanding of the mechanism of this hydroarylation reaction, kinetic isotope effect studies were performed. The experiments on the cyclization of **3**, together with its protio analogue **1b**, and **5** revealed a substantial intermolecular ($k_H/k_D = 2.6$) and intramolecular ($k_H/k_D = 3.5$) kinetic isotope effect (Scheme 3). These data are in the range of the the isotope effects found in the Pd-catalyzed arylations proceeding *via* C–H activation pathways.[11] Based on these observations, we propose the following mechanism for this reaction (Scheme 4). According to the

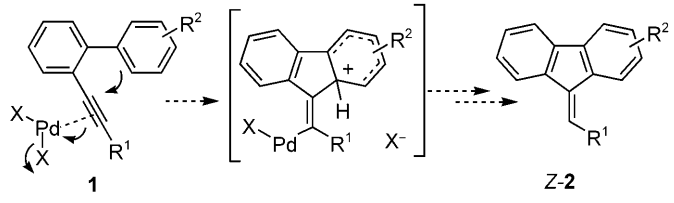


Scheme 3.



Scheme 4.

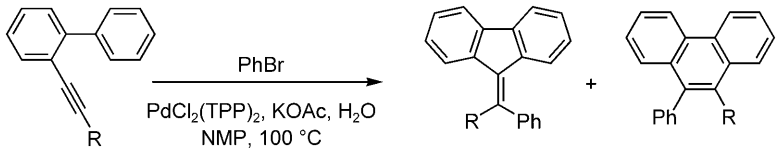
path **a**, upon the *ortho*-palladation of **1**, the intermediate **8** is produced, which undergoes a migratory insertion to the triple bond to give a vinylpalladium species **9**. Protiodepalladation of intermediate **9** produces fluorene **2** and regenerates the catalyst. Alternative pathway (path **b**) involves the formation of palladium hydride species **10**, which upon carbopalladation of the triple bond produces intermediate **11**. Consecutive reductive elimination gives the desired fluorenone **2**. However, this pathway is considered to be less likely due to a substantial loss of the deuterium observed in the cyclization of **3**.[12] The Friedel–Crafts-type mechanism, which potentially could account for the cyclization of **1**, was ruled out based on both the higher propensity of the electron-deficient biaryls in this hydroarylation reaction and the high values of the obtained kinetic isotope effects. The observed stereoselectivity of reaction also contradicts with the electrophilic mechanism. It should be mentioned that, according to the literature reports,[3–6,8] the Friedel–Crafts cyclization of biaryl **1** should proceed in a *trans*-fashion, resulting in the formation of (*Z*)-fluorene (Scheme 5). However, the hydroarylation reaction, described herein, produces fluorenes with the alternative geometry of the double bond, thus strongly supporting the *cis*-cyclization pathway (Table 1, Scheme 4).



Scheme 5.

Encouraged by the successful hydroarylation of *o*-alkynylbiaryls leading to the fluorene framework, we envisioned the cascade intermolecular arylation/annulations of *o*-alkynylbiaryls with aryl halides as an attractive approach toward densely substituted fluorenes. It should be mentioned that the Pd-catalyzed arylation/annulation approach has been extensively explored by Larock for the synthesis of polycyclic aromatic compounds.[13] However, the annulation step in most of the reported transformations followed the electrophilic path.[14] Consequently, we were eager to learn whether a possible cascade arylation/annulation reaction of *o*-alkynylbiaryls would follow the C–H activation reaction path. Accordingly, the transformation of different *o*-alkynylbiaryls **1**, in the presence of phenyl bromide, was studied under one of the typical conditions for Pd-catalyzed arylation reactions.[14,15] Thus, cyclization of **1a** produced a 58:42 mixture of the 5-*exo-dig* cyclization product **12** and the 6-*endo-dig* adduct **13** in 90% combined yield (Table 2, entry 1). Similarly, cyclization of *o*-alkynylbiaryls **1m**, **1t**, and **1u** produced comparable mixtures of regioisomers **12** and **13** (Table 2, entries 2–4). Notably, arylation/annulation of alkyl derivative **1v** was highly regioselective, producing fluorene **12** as a sole reaction product in good yield (entry 5). In contrast, cyclization of **1w**, possessing an ester functionality at the alkyne moiety, exhibited reverse regiochemistry[16] producing phenanthrene **13** selectively, albeit in low yield (Table 2, entry 6).

Table 2. Arylative cyclization of *o*-alkynylbiaryls.



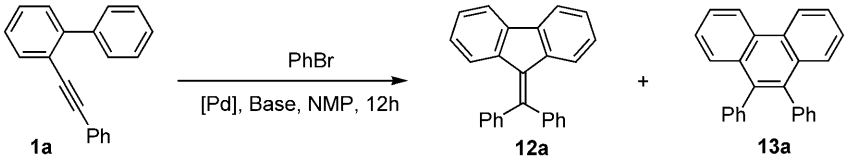
1a, **1m**, **1t – w** **12** **13**

#	R	Substrate	**12**:**13** Ratio[a]	Combined yield[b] [%]
1	Ph	**1a**	58:42	90
2	*p*-OMe(C_6H_4)	**1m**	72:28	70
3	*p*-CN(C_6H_4)	**1t**	51:49	65
4	*p*-COMe(C_6H_4)	**1u**	53:47	60
5	*n*-Bu	**1v**	100:0	70
6	CO_2Et	**1w**	0:100	30

[a] Product ratios determined by GC/MS analysis.
[b] Isolated yields.

Next, we performed an optimization of the reaction conditions aiming at the development of a selective cascade arylation/annulation protocol towards **12** (Table 3). Aryl-substituted **1a**, which produced nearly equal amounts of regioisomeric products (Table 2), was chosen for optimization studies. It was found that employment of bidentate phosphine ligands caused much more selective cyclization of **1a** into **12a**. Expectedly, performing reactions in the presence of $Pd(OAc)_2$/d-*i*-Prpf led to a more selective reaction. Finally, use of this catalyst system in the presence of DABCO allowed for obtaining **12a** as a sole regioisomer in nearly quantitative yield (Table 3).

Table 3. Optimization of conditions for arylative cyclization of **1a**.

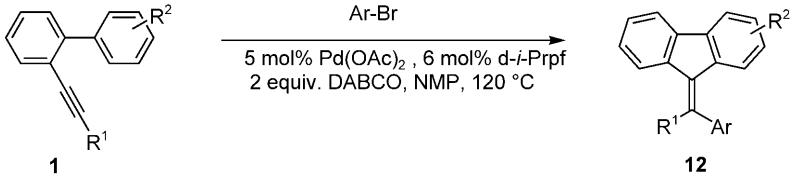


1a **12a** **13a**

#	[Pd] source	Ligand	Base	Temperature	**12a**:**13a** Ratio[a]	Yield of **12a** [%][b]
1	$Pd(OAc)_2$	dppp	KOAc	120	–	0
2	$Pd(OAc)_2$	dppe	KOAc	120	–	0
3	$Pd(OAc)_2$	$Ph_2P(CH_2)_5PPh_2$	KOAc	120	–	0
4	$Pd(OAc)_2$	dppf	KOAc	100	90:10	10
5	$Pd(OAc)_2$	d-*t*-Bupf	KOAc	100	90:10	12
6	$Pd(OAc)_2$	d-*i*-Prpf	KOAc	120	95:5	12
7	$Pd(OAc)_2$	d-*i*-Prpf	Cs_2CO_3	120	–	0
8	$Pd(OAc)_2$	d-*i*-Prpf	Et_3N	120	99:1	45
9	$Pd(OAc)_2$	d-*i*-Prpf	EtN(*i*-Pr)$_2$	120	100:0	60
10	$PdCl_2$	d-*i*-Prpf	EtN(*i*-Pr)$_2$	120	100:0	31
11	$Pd(dba)_2$	d-*i*Prpf	EtN(*i*-Pr)$_2$	120	100:0	20
12	$PdCl_2(CH_3CN)_2$	d-*i*-Prpf	EtN(*i*-Pr)$_2$	120	100:0	30
13	$Pd(OAc)_2$	d-*i*-Prpf	Bu_4NBr	120	100:0	20
14	$Pd(OAc)_2$	d-*i*-Prpf	DABCO	100	100:0	70[c]
15	$Pd(OAc)_2$	dppf	DABCO	110	100:0	81
16	$Pd(OAc)_2$	d-*t*-Bupf	DABCO	110	100:0	80
17	**$Pd(OAc)_2$**	**d-*i*-Prpf**	**DABCO**	**110**	**100:0**	**95**
18	**$Pd(OAc)_2$**	**d-*i*-Prpf**	**DABCO**	**120**	**100:0**	**89**[d]

[a] Product ratios determined by GC/MS analysis.
[b] Yield determined by GC/MS analysis.
[c] Yield after 24 h.
[d] Isolated yield after 6 h.

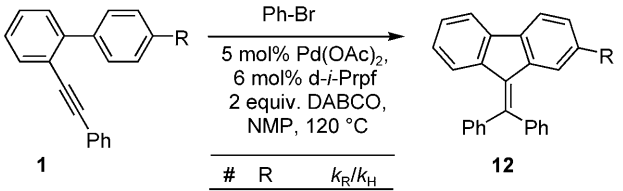
Table 4. Arylative cyclization of *o*-alkynylbiaryls.



#	Substrate	Product	Time [h]/ Yield [%]	#	Substrate	Product	Time [h]/ Yield [%]
1	**1a**	**12a**	6/89	7	**1y**	**12g**	10/76
2	**1m**	**12b**	9/86	8	**1c**	**12h**	4.5/88
3	**1x**	**12c**	24/81	9	**1i**	**12i**	6/85
4	**1b**	**12d**	12/84	10	**1z**	**12j**	8/86[c]
5	**1o**	**12e**	12/86	11	**1g**	**12k**	8/89[c]
6	**1o**	**12f**	12/85	12	**1m**	**12l**	12/80[c]

[a] *Reaction conditions:* 0.5 mmol of **1**, 0.025 mmol of $Pd(OAc)_2$, 0.035 mmol of d-*i*-Prpf, 1 mL of toluene, 120 °C.
[b] Isolated yields after recrystalization.
[c] Toluene was used as a solvent.

After the efficient conditions for cascade arylation of **1** into **12** had been identified, the generality of this transfromation was examined (Table 4). It was found that the cascade arylation/annulation appeared to be quite general with respect to both *o*-alkynylbiaryl and aryl halide used producing fluorenes **12** in high yields. Introduction of electron-withdrawing substituents at either of reactants usually slightly facilitated the reaction (entries 8, 9, 10, and 11), whereas more electron-rich substrates reacted somewhat slower (entries 2, 4, and 7). Pyridine-containing substrate **1o** reacted comparably well producing heteroaryl-substituted fluorenes **12d**,**e** (entries 5, 6). The reaction was substantially slower with sterically more hindered **1x**, possessing a methyl group at the *ortho*-position (entry 3).

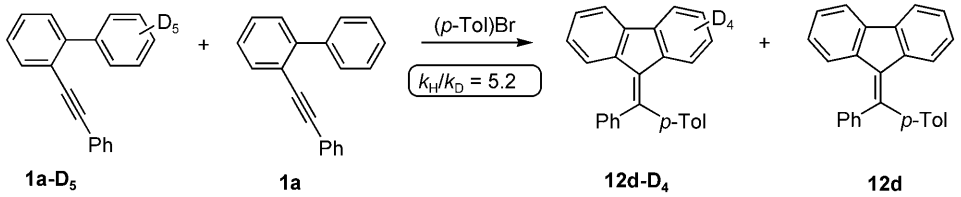


#	R	k_R/k_H
1	OMe	0.7
2	H	1.0
3	CF_3	1.4

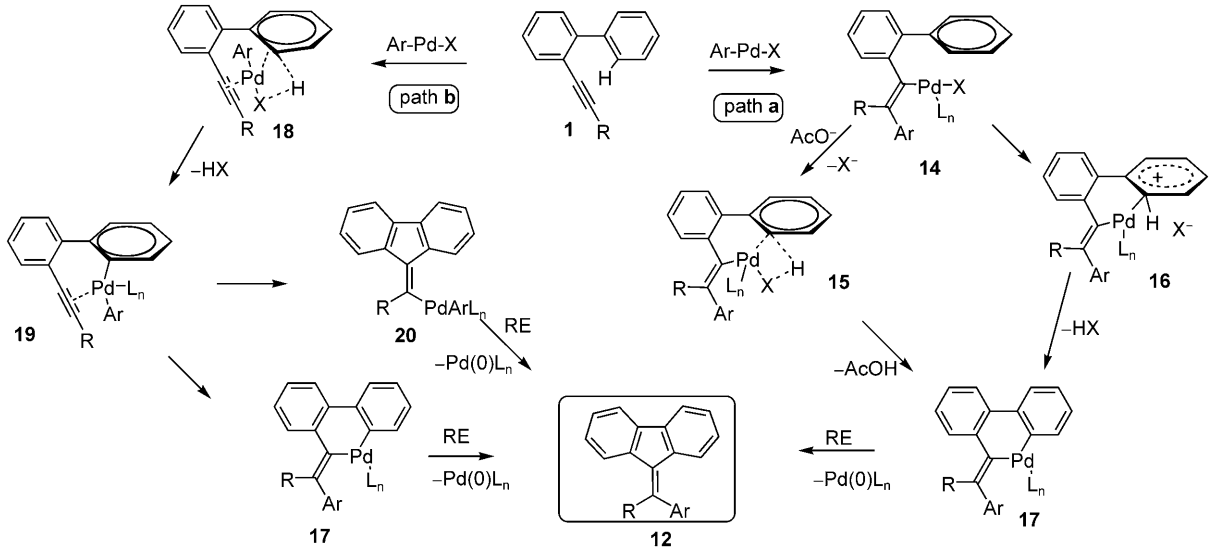
Figure 1.

Although the results in Table 4 indicate faster reaction of biaryls possessing electron-withdrawing substituents at the adjacent phenyl ring (entries 1, 7, and 8), we found clarification of this question quite important and thus set up a competitive reactivity studies (Figure 1). It was found that, at early stage of the reaction (*ca.* 25% conversion), MeO-containing **1y** reacted about 1.5 times slower and CF_3-containing **1c** 1.4 times faster than the unsubstituted substrate **1a** (Figure 1). This trend, like that in the hydroarylation reaction (*vide supra*), strongly contradicts with possible electrophilic character of the cyclization step.[3–6,8] Furthermore, the intermolecular deuterium/hydrogen isotope effect studies of the cascade arylation of **1a** and its deuteriated analogue with phenyl bromide revealed a profound isotope effect of 5.2 (Scheme 6). This value is in a good agreement with the reported data of the isotope effect in the Pd-catalyzed arylations proceeding *via* a C–H activation mechanism.[11]

Based on the above-mentioned results, we propose the following rationale for the Pd-catalyzed cascade arylation/annulation of *o*-alkynylbiaryls **1** into fluorenes **12** (Scheme 7). ArPdX, upon regioselective carbopalladation of triple bond[17] of **1**, produces a vinylpalladium species **14**. The latter, upon a direct[18] or a ligand-assisted[19] C–H activation (**15**) with subsequent loss of HX produces the palladacycle **17**. Re-



Scheme 6.



Scheme 7.

ductive elimination of **17** furnishes the fluorene product **12** (Scheme 7, path **a**). Alternatively, the vinylpalladium species **14** may undergo an elecrophilic aromatic substitution (**16**) to give palladacycle **17**. However, on the basis of the substantial isotope effect values and higher propensity of electron-deficient arenes towards cyclization (*vide supra*), this path was considered to be less likely. Although less plausible, a triple bond-coordinated[20,21] ArPdX (**18**) entity may undergo a direct insertion into the C–H bond to produce a bis-arylpalladium species **19** (path **b**). Intramolecular migratory insertion of either of the Ar–Pd bonds into the triple bond (**20** or **17**), followed by reductive elimination, produces **12**.

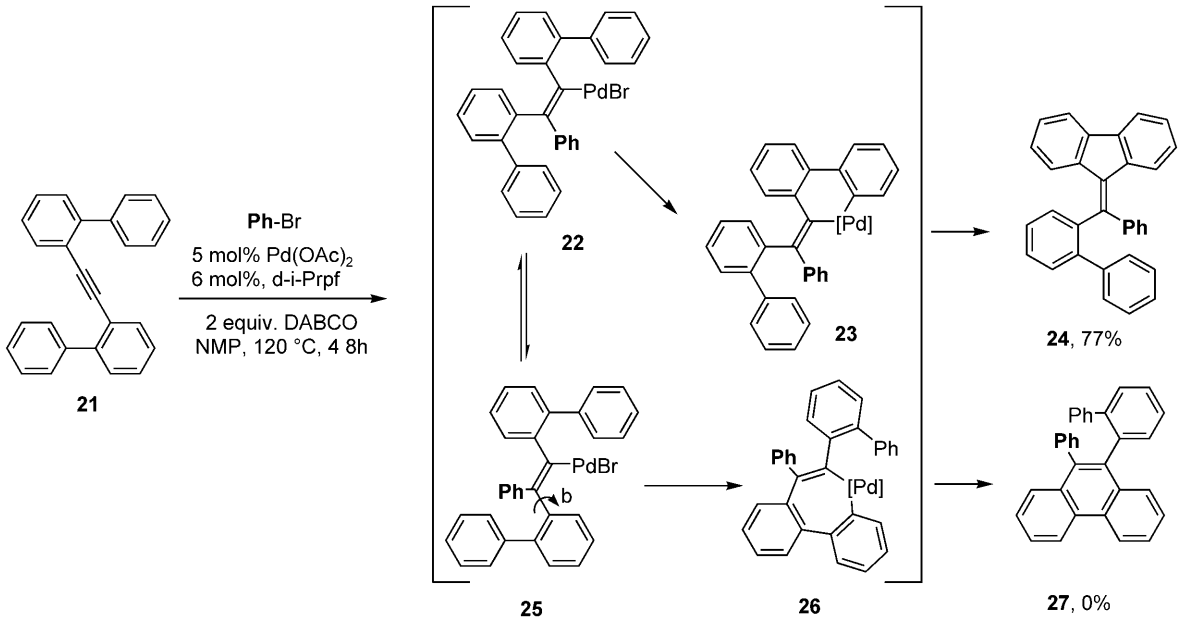
We were intrigued to learn whether the observed exclusive 5-*exo-dig* annulation for this cascade reaction is specific for the $Pd(OAc)_2$/d-*i*-Prpf catalytic system. In other words, what would happen if, by design, the vinylpalladium intermediate of type **14** would have a choice to cyclize into 5- and 6-membered ring? To this end, a bis-biphenyl alkyne **21** was synthesized. It was reasoned that, upon carbopalladation of the triple bond, a vinylpalladium intermediate **22** would form. It can undergo a C–H insertion into the adjacent phenyl ring to form the pallacycle **23**, which, after reductive elimination, would produce the fluorene derivative **24**. Alternatively, **22**, *via* a well-precedented double bond isomerization,[22] may form **25**, which is set for an insertion into the C–H bond of a distinct aryl ring to produce **26**, and, upon reductive elimination, the phenanthrene derivative **27** (Scheme 8). The experiment showed that, upon standard reaction conditions, the fluorene **24** was formed as a single reaction product, thus supporting a strong preference of this catalytic system for 5-*exo-dig* reaction pathway.

Conclusions

In conclusion, we have developed a set of methodologies for efficient construction of fluorene framework from *o*-alkynyl biaryls in the presence of $Pd(OAc)_2$/d-*i*-Prpf catalytic system. The intramolecular hydroarylation of *o*-alkynylbiaryls provides easy access to fluorenes with defined geometry. Alternative intermolecular cascade arylation/annulation method allows for efficient synthesis of fluorenes, fully substituted at C-10. It was shown that, regardless of the substitution pattern, these methods proceed exclusively *via* a 5-*exo-dig* cyclization motif. Mechanistic studies, including product and hydrogen/deuterium isotope effect studies, strongly support a C–H activation path for the key annulation step in both transformations.

Experimental Section

NMR spectra were recorded on Bruker Avance DRX-500 (500 MHz) or DPX-400 instruments. (+) and (–) represent positive and negative signals in ^{13}C DEPT-135 experiments. GC/MS analysis was performed on a Hewlett Packard Model 6890 GC interfaced to a Hewlett Packard Model 5973 mass selective detector (15 m × 0.25 mm capillary column, HP-5MS). HPLC analysis was performed using a Gilson 321 pump interfaced with a Gilson Holochrome variable band UV detector tuned for 254 nm. A Chiralcel OD-H column (250 × 4.6 mm) was used for chiral HPLC analysis. Column chromatography was carried out employing Silicy-



Scheme 8.

cle Silia-P Flash silica gel (40–63 μm). Precoated silica gel plates F-254 were used for thin-layer analytical chromatography. Anhydrous solvents were purchased from Aldrich and stored over calcium hydride. Alkynes and metal catalysts were commercially available and purchased from Aldrich, Strem Chemicals Inc. or Acros Organics, or synthesized *via* known literature procedures.

General Procedure Synthesis of *o*-Alkynylbiaryl Compounds 1a–z (Table 1)

A round-bottom flask containing a stirring bar was charged with $(Ph_3P)_2PdCl_2$ (70.1 mg, 0.1 mmol), arylboronic acid (2.6 mmol), *o*-alkynylaryl bromide (2 mmol) and Na_2CO_3 (424 mg, 4 mmol). The flask was sealed with rubber septum, evacuated and backfilled with argon. Toluene (10 mL) was added through the septum *via* syringe together with EtOH (5 mL) and water (5 mL). The reaction mixture was placed into 70 °C preheated oil bath and heated at this temperature for 1 to 3 h until judged complete by GC/MS analysis. The content was cooled down to room temperature, diluted with 10 mL of EtOAc and 10 mL of water and transferred into a separatory funnel. The organic layer was separated, washed with water (2×20 mL), dried over $MgSO_4$. The solvent was evaporated under reduced pressure and resulting residue was purified by column chromatography on a silica gel with hexanes or 20:1 hexanes/DCM system to afford the *o*-alkynylbiaryl.

2-[(4-Methylphenyl)ethynyl]-4′-(trifluoromethyl)biphenyl (1d): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.75–7.83 (m, 2H), 7.71 (s, 2H), 7.67 (d, *J* = 7.52 Hz, 1H), 7.34–7.47 (m, 3H), 7.17–7.23 (m, 2H), 7.12 (s, 2H), 2.35 (s, 3H);^{13}C NMR (126 MHz, $CDCl_3$): δ = 144.2, 142.2, 138.6, 132.9 (+), 131.2 (+), 129.7 (+), 129.3 (+), 129.1 (+), 128.5 (+), 127.8 (+), 124.8 (+), 121.9, 120.0, 93.1, 88.0, 21.5 (+).

5-Fluoro-2-methyl-2′-(4-methylphenyl)-ethynylbiphenyl (1f): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.64 (dd, *J* = 6.60, 1.65 Hz, 1H), 7.33–7.42 (m, 3H), 7.31 (dd, *J* = 7.15, 1.65 Hz, 1H), 7.16 (s, 3H), 7.04–7.11 (m, 3H), 2.38 (s, 3H), 2.33 (s, 3H);^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.0, 157.1, 138.4, 138.2, 132.8, 132.4 (+), 132.1 (+), 131.3 (+), 130.1 (+), 129.8 (+), 129.7 (+), 129.0 (+), 127.9 (+), 127.6 (+), 123.1, 120.3, 115.3 (+), 115.1 (+), 92.5, 88.1, 21.5 (+), 20.0 (+).

3′,5′-Difluoro-2-[(4-methylphenyl)ethynyl]biphenyl (1g): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.65 (d, *J* = 6.97 Hz, 1H), 7.34–7.44 (m, 3H), 7.27 (s, 2H), 7.20–7.25 (m, 2H), 7.14 (s, 2H), 6.85 (s, 1H), 2.36 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 163.6 (d, *J* = 12.9 Hz), 161.6 (d, *J* = 12.9 Hz), 143.7, 141.2, 138.6, 133.0, 132.8 (d, *J* = 90.6 Hz, +), 131.6 (+), 131.2 (+), 129.2 (+), 128.5 (+), 128.0, 120.9 (d, *J* = 232.1 Hz), 112.4 (d, *J* = 25.9 Hz, +), 102.7 (t, *J* = 25.4 Hz, +), 93.5, 87.8, 21.5 (+).

4-[3′,5′-Bis(trifluoromethyl)biphenyl-2-yl]ethynylbenzonitrile (1h): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.12 (s, 2H), 7.93 (s, 1H), 7.73 (s, 1H), 7.59 (s, 2H), 7.50–7.56 (m, 1H), 7.48 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 142.2, 140.8, 140.4, 133.7 (+), 132.0 (+), 131.8 (+), 131.6 (+), 131.4 (+), 129.8 (+), 129.5 (+), 128.7, 127.4, 124.4, 121.4 (+), 120.7 (+), 118.5 (+), 118.4 (+), 111.9 (+), 92.0, 91.5 (+).

2-(4-Methylphenyl)ethynyl-3′,5′-bis(trifluoromethyl)biphenyl (1k): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.16 (s, 2H), 7.91 (s, 1H), 7.70 (s, 1H), 7.40–7.48 (m, 3H), 7.23 (d, *J* = 8.07 Hz, 2H), 7.12 (d, *J* = 7.89 Hz, 2H), 2.35 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 142.5, 140.3, 138.8, 133.3 (+), 131.3 (+), 130.3 (+), 129.9 (+), 129.5 (+), 129.3 (+), 129.1 (+), 128.7 (+), 128.5, 124.5, 122.4, 122.0, 121.2, 119.5, 93.7, 87.1, 21.5 (+).

3-{[4′-(Trifluoromethyl)biphenyl-2-yl]ethynyl}pyridine (1o): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.57 (s, 1H), 8.52 (d, *J* = 5.68 Hz, 1H), 7.67–7.80 (m, 4H), 7.55–7.60 (m, 1H), 7.38–7.50 (m, 3H), 7.21–7.29 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 152.0 (+), 148.7 (+), 144.0, 142.6, 138.1 (+), 133.2 (+), 129.7 (+), 129.5 (+), 129.2 (+), 127.9 (+), 124.9 (+), 123.2, 123.0, 121.0, 91.9, 89.3.

Pd-Catalyzed Cyclization of *o*-Alkynylbiaryls; Representative Procedure

An oven-dried 3-mL Wheaton vial containing a stirring bar was charged with **1** (0.5 mmol), $Pd(OAc)_2$ (5.6 mg, 0.025 mmol) and 1,1′-bis(di-*iso*-propylphosphino)ferrocene (146 mg, 0.035 mmol) under an N_2 atmosphere. Dry toluene (1 mL) was added and the reaction vessel was capped with pressure screw cap. The reaction mixture was heated at 120 °C for 2 h (when judged complete by GC/MS analysis). The resulting mixture was cooled down to room temperature and filtered through a short SiO_2 plug with the aid of DCM. The filtrate was concentrated under reduced pressure and the residue was purified by chromatography on a silica gel column (20:1 hexanes/DCM) affording the benzylidene-9*H*-fluorene.

9-Benzylidene-9*H*-fluorene (2a):[23] ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.81 (1H, d, *J* = 7.52 Hz), 7.70–7.77 (4H, m), 7.60 (4H, s), 7.48 (3H, t, *J* = 7.43 Hz), 7.38–7.44 (3H, m), 7.30–7.38 (3H, m), 7.08 (1H, dt); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 141.27, 139.50, 139.21, 136.92, 136.57 (+), 136.50 (+), 129.28 (+), 128.56 (+), 128.23 (+), 128.04 (+), 127.29 (+), 127.00 (+), 126.68 (+), 124.43 (+), 120.26 (+), 119.73 (+), 119.61 (+).

9-(4-Methylbenzylidene)-9*H*-fluorene (2b):[24] ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.80 (d, *J* = 7.34 Hz, 1H), 7.73 (d, *J* = 7.52 Hz, 2H), 7.68 (s, 2H), 7.51 (s, 2H), 7.36–7.41 (m, 1H), 7.30–7.36 (m, 2H), 7.28 (s, 3H), 7.06–7.12 (m, 1H), 2.45 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 141.17, 139.63, 139.08, 138.00, 136.64 (+), 135.99 (+), 133.87 (+), 129.28 (+), 129.23 (+), 128.39 (+), 128.03 (+), 127.54 (+), 126.93 (+), 126.61 (+), 124.38 (+), 120.17 (+), 119.68 (+), 119.55 (+), 21.46 (+).

(9*E*)-9-Benzylidene-2-(trifluoromethyl)-9*H*-fluorene (2c): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.03 (1H, s), 7.76–7.83 (3H, m), 7.47–7.52 (2H, m), 7.41–7.46 (1H, m), 7.35–7.39 (1H, m), 7.13–7.18 (1H, m); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 142.09, 139.81, 139.69, 137.11, 136.27, 135.42, 129.23, 129.03 (+), 128.82 (+), 128.66 (+), 128.46 (+), 127.81 (+), 125.07 (+), 125.04 (+), 124.53 (+), 120.44 (+), 119.69 (+), 117.32 (+); HR-MS (EI): *m/z* = 322.09712, calcd. for $C_{21}H_{13}F_3$: 322.09694.

(9*E*)-9-(4-Methylbenzylidene)-2-(trifluoromethyl)-9*H*-fluorene (2d): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.02 (s, 1H), 7.70–7.85 (m, 4H), 7.63 (d, 1H), 7.51 (d, *J* = 7.89 Hz, 2H), 7.36 (t, *J* = 7.45 Hz, 1H), 7.29 (d, *J* = 7.75 Hz, 2H), 7.16 (t, *J* = 7.60 Hz, 1H), 2.45 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 141.94, 139.81, 139.73, 138.55, 137.20, 134.89 (+), 131.75, 129.34 (+), 129.27 (+), 127.74 (+), 124.87 (+), 124.48 (+),

120.39 (+), 119.64 (+), 117.23 (+), 21.48 (+); HR-MS (EI): m/z = 336.1128, calcd. for $C_{22}H_{15}F_3$: 336.1126.

Ethyl (2*E*)-(1,3-difluoro-9*H*-fluoren-9-ylidene)acetate (2e): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.83 (d, J = 7.89 Hz, 1H), 7.61 (d, J = 7.34 Hz, 1H), 7.41–7.46 (m, 1H), 7.36–7.40 (m, 1H), 7.16 (dd, J = 7.79, 2.11 Hz, 1H), 7.09 (d, J = 4.03 Hz, 1H), 4.35 (q, J = 7.15 Hz, 2H), 1.40 (t, J = 7.15 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 166.3, 165.4, 163.3, 161.1, 159.1, 144.6, 140.5 (+), 135.8 (+), 130.6 (+), 129.2 (+), 128.8 (+), 120.0 (+), 119.3 (+), 103.4–103.9, 103.2 (+), 60.9 (+), 14.3 (+); HR-MS (EI): m/z = 286.0813, calcd. for $C_{17}H_{22}F_2O_2$: 286.0806.

(9*E*)-4-Fluoro-1-methyl-9-(4-methylbenzylidene)-9*H*-fluorene (2f): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.93 (d, J = 7.52 Hz, 1H), 7.83 (s, 1H), 7.40 (s, 3H), 7.29 (s, 3H), 6.92–7.10 (m, 3H), 2.68 (s, 3H), 2.46 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 158.14 (+), 156.17 (+), 138.45 (+), 138.32 (+), 137.91 (+), 136.72 (+), 134.49 (s, 1C), 133.22 (+), 131.39 (s, 1 C), 131.34 (s, 1 C), 129.91 (s, 1 C), 129.56 (s, 1 C), 129.35 (s, 1 C), 128.95 (s, 1 C), 128.42 (s, 1 C), 126.42 (s, 1 C), 124.39 (s, 1 C), 114.48 (s, 1 C), 114.32 (s, 1 C), 21.81 (s, 1 C), 21.42 (s, 1 C); HR-MS (EI): m/z = 300.1313, calcd. for $C_{22}H_{17}F$: 300.1314.

(9*E*)-1,3-Difluoro-9-(4-methylbenzylidene)-9*H*-fluorene (2g): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.98 (d, J = 2.75 Hz, 1H), 7.67 (d, J = 7.52 Hz, 1H), 7.56 (d, J = 7.89 Hz, 1H), 7.45 (d, J = 7.89 Hz, 2H), 7.32 (dt, J = 7.52, 0.92 Hz, 1H), 7.28 (s, 1H), 7.24 (dd, J = 7.98, 2.11 Hz, 1H), 7.12 (dd, J = 15.22, 1.10 Hz, 1H), 6.78 (dt, J = 11.00, 9.17, 2.20 Hz, 1H), 2.45 (s, 3H); ^{13}C NMR (500 MHz, $CDCl_3$): δ = 162.8 (dd, J = 248.8, 11.1 Hz), 159.4 (dd, J = 253.4, 12.9 Hz), 142.9, 139.6, 138.2, 137.4 (+), 134.0 (+), 133.5 (+), 129.8 (+), 129.3 (+), 129.0 (+), 128.3 (+), 127.8 (+), 124.6 (+), 121.5 (+), 120.1 (+), 10.8 (+), 21.4 (+); HR-MS (EI): m/z = 305.1142, calcd. for $C_{21}H_{14}F_2$: 305.1151.

4-(*E*)-[1,3-Bis(trifluoromethyl)-9*H*-fluoren-9-ylidene]methylbenzonitrile (2h): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.1 (d, J = 13.9 Hz), 7.9 (s), 7.8 (s), 7.6–7.7 (m), 7.4 (s), 7.0–7.2 (m); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 143.19, 141.74, 138.55, 138.24, 136.47, 135.92, 134.17, 132.64 (+), 129.53 (+), 129.39 (+), 128.56 (+), 124.81 (+), 122.09 (+), 120.17 (+), 119.84 (+), 118.51 (+), 112.33 (+), 91.16 (+); HR-MS (EI): m/z = 415.0798, calcd. for $C_{23}H_{11}F_6N$: 415.0795.

(9*Z*)-3-(Trifluoromethyl)-9-[4-(trifluoromethyl)benzylidene]-9*H*-fluorene (2i): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.94 (br. s., 1H), 7.82 (d, J = 7.34 Hz, 1H), 7.72–7.79 (m, 4H), 7.68 (s, 2H), 7.45–7.51 (m, 2H), 7.38–7.45 (m, 1H), 7.34 (s, 1H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 141.9, 140.1, 138.8, 139.4, 138.1, 137.0, 130.6 (+), 129.5 (+), 129.1 (+), 128.1 (+), 127.3, 125.7 (+), 124.4 (+), 123.7 (+), 123.1, 122.9, 121.0 (+) 120.6 (+), 116.7 (+); HR-MS (EI): m/z = 390.0841, calcd. for $C_{22}H_{12}F_6$: 390.0843.

(9*E*)-9-Benzylidene-1,3-difluoro-9*H*-fluorene (2j): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.0 (d, J = 2.9 Hz), 7.7 (d, J = 7.7 Hz), 7.5 (s), 7.4–7.5 (m), 7.3 (s), 7.2 (s), 7.1 (s), 6.7–6.8 (m); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 139.66, 137.31, 137.03, 134.07, 133.14, 133.04, 128.98 (+), 128.58 (+), 128.45 (+), 128.21 (+), 128.15 (+), 127.93 (+), 127.83 (+), 124.67 (+), 120.14 (+), 103.09 (+), 102.88 (+), 102.74 (+), 102.53; HR-MS (EI): m/z = 290.09019, calcd. for $C_{20}H_{12}F_2$: 290.09071.

9-(4-Methylbenzylidene)-1,3-bis(trifluoromethyl)-9*H*-fluorene (2k): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.22 (s, 1H), 8.16 (s, 1H), 7.90 (s, 1H), 7.78 (d, J = 7.60 Hz, 1H), 7.39–7.48 (m, 3H), 7.32–7.39 (m, 1H), 7.27–7.32 (m, 2H), 7.12 (s, 1H), 2.46 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 142.7 (s), 139.2 (s), 138.8 (s), 138.0 (s), 138.0 (s), 137.9 (s), 137.8 (s), 137.2 (s), 133.9 (s), 133.8 (s), 129.5 (s), 128.9 (s), 128.5 (s), 128.2 (s), 124.8 (s), 122.4 (s), 121.8 (s), 119.7 (s), 119.6 (s), 21.5 (s); HR-MS (EI): m/z = 404.0998, calcd. for $C_{23}H_{14}F_6$: 404.1000.

9-(4-Nitrobenzylidene)-9*H*-fluorene (2l):[25] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.32 (s, 2H), 7.66–7.85 (m, 5H), 7.60 (s, 1H), 7.42 (s, 2H), 7.35 (s, 2H), 7.07 (t, J = 7.53 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 147.2, 144.0, 141.8, 139.5, 138.9, 138.9, 135.8, 130.2 (+), 129.5 (+), 129.1 (+), 127.3 (+), 127.0 (+), 124.3 (+), 123.9 (+), 120.6 (+), 120.1 (+), 119.8 (+); HR-MS (EI): m/z = 300.1025, calcd. for $C_{20}H_{13}NO_2$: 300.1025.

4-(9*H*-Fluoren-9-ylidenemethyl)phenyl methyl ether (2m):[25] ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.79 (d, J = 7.52 Hz, 1H), 7.73 (s, 3H), 7.66 (s, 1H), 7.56 (d, J = 8.44 Hz, 2H), 7.29–7.42 (m, 3H), 7.10 (t, J = 7.61 Hz, 1H), 7.00 (d, J = 8.80 Hz, 2H), 3.90 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.56, 141.11, 139.70, 138.97, 136.64, 135.48, 130.87 (+), 129.12, 128.29 (+), 127.89 (+), 127.34 (+), 126.89 (+), 126.59 (+), 124.19 (+), 120.08 (+), 119.70 (+), 119.53 (+), 113.95 (+), 55.36 (+); HR-MS (EI): m/z = 284.1202, calcd. for $C_{21}H_{16}O$: 284.1201.

Methyl (9*E*)-9-benzylidene-9*H*-fluorene-2-carboxylate (2n): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.48 (s, 1H), 8.09 (d, J = 8.04 Hz, 1H), 7.72–7.89 (m, 3H), 7.62 (s, 2H), 7.30–7.56 (m, 3H), 7.15 (s, 1H), 3.98 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 167.3, 143.2, 140.1, 139.5, 137.5, 136.5 (+), 135.6 (+), 129.7 (+), 129.3 (+), 128.8 (+), 128.6 (+), 128.3 (+), 127.8 (+), 125.8, 124.5 (+), 121.7 (+), 120.6 (+), 120.4, 119.3 (+), 52.2 (+); HR-MS (EI): m/z = 312.1149, calcd. for $C_{22}H_{16}O_2$: 312.1150.

3-(9*H*-Fluoren-9-ylidenemethyl)pyridine (2o): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.87 (s, 1H), 8.68 (dd, J = 4.86, 1.38 Hz, 1H), 8.03 (s, 1H), 7.82 (d, J = 7.89 Hz, 1H), 7.78 (d, J = 7.70 Hz, 1H), 7.67 (s, 2H), 7.48 (d, J = 7.89 Hz, 1H), 7.43 (dd, J = 7.89, 4.95 Hz, 1H), 7.39 (s, 1H), 7.12–7.18 (m, 1H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 150.1 (+), 149.4 (+), 142.3, 140.1, 139.2, 137.4, 136.7 (+), 136.4 (+), 132.3, 129.4 (+), 128.1 (+), 125.6, 124.4 (+), 124.3 (+), 123.4 (+), 120.7 (+), 119.8 (+), 117.5 (+); HR-MS (EI): m/z = 323.09245, calcd. for $C_{20}H_{13}F_3N$: 323.09463.

(9*E*)-2-Fluoro-4-methyl-9-(4-methylbenzylidene)-9*H*-fluorene (2p): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.80 (d, J = 7.70 Hz, 1H), 7.68 (d, J = 7.70 Hz, 1H), 7.61 (s, 1H), 7.48 (d, J = 7.89 Hz, 2H), 7.27–7.35 (m, 4H), 7.05 (s, 1H), 6.88 (s, 1H), 2.69 (s, 3H), 2.45 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 162.1 (d, J = 244.1 Hz), 141.5, 138.2, 137.1, 135.5, 134.6, 133.6, 133.1, 129.3 (d, J = 8.3 Hz, +), 128.5 (+), 128.1 (+), 125.9, 125.6 (+), 124.1 (+), 122.4 (+), 117.2 (d, J = 22.2 Hz, +), 104.7 (d, J = 23.1 Hz, +), 21.4 (+), 21.0 (+); HR-MS (EI): m/z = 305.1142, calcd. for $C_{21}H_{14}F_2$: 305.1151.

(9*E*)-9-Benzylidene-1,4-dimethyl-9*H*-fluorene (2q): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.86 (s, 2H), 7.51 (s, 2H), 7.43–7.48 (m, 2H), 7.40 (s, 1H), 7.29 (s, 2H), 7.06 (s, 2H), 6.97 (s, 1H), 2.71 (s, 6H); ^{13}C NMR (126 MHz, $CDCl_2$): δ = 141.7, 139.0, 138.2, 137.9, 137.6, 136.5, 131.5 (+), 131.5,

130.7, 130.4 (+), 129.0 (+), 128.6 (+), 128.0 (+), 127.6 (+), 125.6 (+), 124.5 (+), 122.8 (+), 22.5 (+), 21.2 (+); HR-MS (EI): $m/z = 282.1409$, calcd. for $C_{22}H_{18}$: 282.1410.

(9*Z*)-3-Methoxy-9-(4-methoxybenzylidene)-9*H*-fluorene (2r): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 7.77$ (d, $J = 7.15$ Hz, 1H), 7.69 (s, 1H), 7.62 (d, $J = 8.62$ Hz, 1H), 7.53 (s, 3H), 7.30–7.40 (m, 2H), 7.24 (s, 1H), 6.99 (d, $J = 8.80$ Hz, 2H), 6.65 (s, 1H), 3.89 (s, 6H); ^{13}C NMR (126 MHz, $CDCl_3$): $\delta =$ 160.3, 159.4, 142.9, 140.6, 138.7, 135.0, 130.8 (+), 129.6, 129.3, 127.8 (+), 127.0 (+), 125.2 (+), 125.1 (+), 120.1 (+), 119.4 (+), 113.9 (+), 112.7 (+), 104.7 (+), 55.5 (+), 55.4 (+); HR-MS (EI): $m/z = 314.1308$, calcd. for $C_{22}H_{18}O_2$: 314.1307.

Mechanistic Studies

9-(4-Methylbenzylidene)-9*H*-fluorene-d_5 (4): A round-bottom flask containing a stirring bar was charged with $(Ph_3P)_2PdCl_2$ (34 mg, 0.05 mmol), phenylboronic acid-d_5 (200 mg, 3.2 mmol), 1-bromo-2-[(4-methylphenyl)ethynyl]-benzene (657 mg, 2.4 mmol) and Na_2CO_3 (424 mg, 4 mmol). The flask was sealed with a rubber septum, evacuated and backfilled with argon. Toluene (4 mL) was added through the septum *via* syringe together with EtOH (1 mL) and water (1 mL). The reaction mixture was placed into 70 °C preheated oil bath and heated at this temperature for 2 h until judged complete by GC/MS analysis. The mixture was cooled down to room temperature, diluted with 10 mL of EtOAc and 10 mL of water and transferred into a separatory funnel. The organic layer was separated, washed with water (2×10 mL), dried over $MgSO_4$. The solvent was evaporated under reduced pressure and resulting residue was purified by column chromatography on a silica gel with hexanes to afford 9-(4-methylbenzylidene)-9*H*-fluorene-d_5 (99% incorporated deuterium). ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 7.65$ (dd, $J = 7.70$, 0.92 Hz, 1H), 7.41–7.48 (m, 1H), 7.37–7.42 (m, 1H), 7.30–7.36 (m, 1H), 7.23 (s, 2H), 7.10 (d, $J = 7.89$ Hz, 2H), 2.34 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): $\delta = 143.7$, 140.4, 138.2, 132.8 (+), 131.2 (+), 129.4 (+), 129.0 (+), 128.3 (+), 127.0 (+), 121.8 , 120.4, 92.4, 88.7, 21.5 (+).

9-Benzylidene-9*H*-fluorene-d_1 (6): A round-bottom flask containing a stirring bar was charged with $(Ph_3P)_2PdCl_2$ (121 mg, 0.173 mmol), phenylboronic acid-d_1 (510 mg, 4.1 mmol), 1-bromo-2-phenylethynylbenzene (546 mg, 3.5 mmol) and Na_2CO_3 (424 mg, 4 mmol). The flask was sealed with a rubber septum, evacuated and backfilled with argon. Toluene (7 mL) was added through the septum *via* syringe together with EtOH (3 mL) and water (3 mL). The reaction mixture was placed into 70 °C preheated oil bath and heated at this temperature for 2 h until judged completed by GC/MS analysis. The mixture was cooled down to room temperature, diluted with 10 mL of EtOAc and 10 mL of water and transferred into a separatory funnel. The organic layer was separated, washed with water (2×10 mL), dried over $MgSO_4$. The solvent was evaporated under reduced pressure and resulting residue was purified by column chromatography on a silica gel with hexanes to afford 9-benzylidene-9*H*-fluorene-d_1 (99% deuterium incorporated). ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 7.64$–7.75 (m, 2H), 7.39–7.53 (m, 5H), 7.23–7.39 (m, 6H); ^{13}C NMR (126 MHz, $CDCl_3$): $\delta = 143.9$, 140.5, 132.9 (+), 131.4 (+), 129.5 (+), 129.4 (+), 128.6 (+), 128.3 (+), 128.1 (+), 127.9 (+), 127.0–127.9 (m), 123.5, 121.6, 92.2, 89.4.

Intermollecular Kinetic Isotope Effect Measurements

A mixture of 20 mg of 9-(4-methylbenzylidene)-9*H*-fluorene-d_5 (0.0732 mmol) and 19.64 mg of 9-(4-methylbenzylidene)-9*H*-fluorene (0.0732 mmol) was placed into an oven-dry 1-mL Weaton vial, with a stir bar. $Pd(OAc)_2$ (1.6 mg, 0.0074 mmol) and 1,1′-bis(di-*iso*-propylphosphino)ferrocene (3.7 mg, 0.009 mmol) were added under an N_2 atmosphere. Dry toluene (292 μL) was added and the reaction vessel was capped with a pressure screw cap. The reaction mixture was heated at 120 °C. Heating was stopped at 25–30% conversion of 9-(4-methylbenzylidene)-9*H*-fluorene as detected by GC/MS analysis. The mixture was allowed to cool down to room temperature and filtered through short SiO_2 plug with aid of DCM. The filtrate was collected and solvent was evaporated under reduced pressure. The resulting mixture was connected to the high vacuum pump, dried, and analyzed by ^{1}H NMR without any further purification. The above experiment was repeated three more times giving the average of $k_H/k_D = 2.6$.

Intramollecular Kinetic Isotope Effect Measurements

An oven-dried 1-mL Wheaton vial containing a stirring bar was charged with 9-benzylidene-9*H*-fluorene-d_1 (30 mg, 0.117 mmol), $Pd(OAc)_2$ (1.32 mg, 0.006 mmol) and (2.94 mg, 0.007 mmol) under an N_2 atmosphere. Dry toluene (240 μL) was added and the reaction vessel was capped with a pressure screw cap. The reaction mixture was heated at 120 °C. When the conversion of 9-benzylidene-9*H*-fluorene-d_1 was detected to be 25–30% (as judged by GC/MS analysis) heating was stopped. The mixture was cooled down to room temperature and filtered through short SiO_2 plug with the aid of DCM. The filtrate was concentrated under the reduced pressure. The residue was dissolved in 2 mL of MeOH. A spatula tip of 10% Pd on carbon was added and the reaction mixture was subjected to the reduction with H_2 at atmospheric pressure. The excess of palladium was removed by filtration through celite. The filtrate was concentrated under reduced pressure. The resulting residue was connected to the high vacuum pump, dried and analyzed by ^{1}H NMR without further purification. The above procedure was repeated two more times, giving the average of $k_H/k_D = 3.5$.

General Procedure for Arylative Cyclization of *o*-Alkynylbiaryls with Aryl Halides (Table 3)

An oven-dried 1-mL Wheaton vial containing a stirring bar was charged with **1** (0.5 mmol), $Pd(OAc)_2$ (5.6 mg, 0.025 mmol), d-*i*-Prpf (13 mg, 0.03 mmol), and DABCO (112 mg, 1 mmol) under an N_2 atmosphere. Dry NMP (1.0 mL) was added followed by the addition of the appropriate aryl halide (0.75 mmol) and the reaction vessel was capped with a pressure screw cap. The reaction mixture was heated at 120 °C until full consumption of starting materials (as judged by GC/MS analysis). The mixture was cooled down to room temperature and filtered through a short SiO_2 plug with the aid of EtOAc. The filtrate was diluted with EtOAc and water. The organic layer was separated, washed

with water (2×10 mL), dried over Na_2SO_4. The solvent was evaporated under reduced pressure, and the resulting crude material was purified by column chromatography on silica gel. The resulting fluorene **12**, was further purified by recrystallization from MeOH.

9-(Diphenylmethylene)-9*H*-fluorene (12a):[26] ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.71 (d, *J* = 7.34 Hz, 2H), 7.34–7.50 (m, 7H), 7.25 (s, 2H), 6.94 (t, *J* = 7.52 Hz, 2H), 6.64 (s, 2H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 145.50, 142.98, 140.49, 138.70, 134.19, 129.67 (+), 128.82 (+), 128.20 (+), 127.62 (+), 126.41 (+), 124.89 (+), 119.24 (+).

4-[9*H*-Fluoren-9-ylidene(phenyl)methyl]phenyl methyl ether (12b): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.72 (dd, *J* = 7.52, 3.12 Hz, 2H), 7.35–7.46 (m, 4H), 7.31 (d, *J* = 8.62 Hz, 2H), 7.21–7.28 (m, 3H), 6.90–7.02 (m, 4H), 6.84 (d, *J* = 7.89 Hz, 1H), 6.63 (d, *J* = 8.07 Hz, 1H), 3.88 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.8, 145.5, 143.3, 140.4, 138.9, 135.3, 133.8, 131.5, 130.0 (+), 128.7 (+), 128.2 (+), 127.4 (+), 127.4 (+), 126.3 (+), 126.3 (+), 124.8 (+), 124.7 (+), 119.2 (+), 114.1 (+), 55.3 (+); HR-MS (EI): *m/z* = 360.1514, calcd. for $C_{27}H_{20}O$: 360.1512.

4-[9*H*-Fluoren-9-ylidene(phenyl)methyl]phenyl methyl ether (12c): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.70 (m, 2H), 7.60–7.46 (m, 4H), 7.31 (d, *J* = 8.62 Hz, 2H), 7.21–7.28 (m, 3H), 6.90–7.02 (m, 4H), 6.84 (m, *J* = 7.89 Hz, 1H), 6.63 (d, *J* = 8.07 Hz, 1H), 2.3 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.8, 145.5, 143.3, 140.4, 138.9, 135.3, 133.8, 131.5, 130.0 (+), 128.7 (+), 128.2 (+), 127.4 (+), 127.4 (+), 126.3 (+), 126.3 (+), 124.8 (+), 124.7 (+), 119.2 (+), 114.1 (+), 21.4 (+); HR-MS (EI): *m/z* = 344.1565, calcd. for $C_{27}H_{22}$: 344.1568.

9-[Phenyl(*p*-tolyl)methylene]-9*H*-fluorene (12d): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.72 (m, 2H), 7.35–7.46 (m, 4H), 7.31 (d, *J* = 8.62 Hz, 2H), 7.21–7.28 (m, 3H), 6.90–7.02 (m, 4H), 6.84 (d, *J* = 7.89 Hz, 1H), 6.63 (d, *J* = 8.07 Hz, 1H), 2.3 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.8, 145.5, 143.3, 140.4, 138.9, 135.3, 133.8, 131.5, 130.0 (+), 128.7 (+), 128.2 (+), 127.4 (+), 127.4 (+), 126.3 (+), 126.3 (+), 124.8 (+), 124.7 (+), 119.2 (+), 114.1 (+), 21.4 (+); HR-MS (EI): *m/z* = 344.1565, calcd. for $C_{27}H_{22}$: 344.1568.

3-[9*H*-Fluoren-9-ylidene(phenyl)methyl]pyridine (12e): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.67 (s, 2H), 7.64–7.74 (m, 3H), 7.33–7.50 (m, 6H), 7.23–7.31 (m, 2H), 6.91–7.00 (m, 2H), 6.59–6.66 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 150.5 (+), 149.2, 142.2, 141.0, 140.8, 140.7, 138.8, 138.3, 138.2 (+), 137.2, 135.7 (+), 129.8 (+), 129.7 (+), 129.2 (+), 129.0 (+), 128.6 (+), 128.2 (+), 126.7 (+), 126.6 (+), 125.0 (+), 124.6 (+), 123.6 (+), 119.5 (+), 119.4 (+); HR-MS (EI): *m/z* = 331.1361, calcd. for $C_{25}H_{17}N$: 331.1357.

3-[9*H*-Fluoren-9-ylidene(3-methylphenyl)methyl] pyridine (12f): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.68 (s, 2H), 7.54–7.82 (m, 3H), 7.05–7.46 (m, 7H), 6.96 (s, 2H), 6.64 (s, 2H), 2.37 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 150.4 (+), 149.2, 142.2, 141.3, 140.8, 140.6, 138.8, 138.4, 138.2, 137.2, 135.5 (+), 130.2 (+), 130.1 (+), 129.3 (+), 129.0 (+), 128.9 (+), 128.1 (+), 126.8 (+), 126.6 (+), 125.1 (+), 124.6 (+), 123.6 (+), 119.5 (+), 119.3 (+), 21.4 (+); HR-MS (EI): *m/z* = 345.1517, calcd. for $C_{26}H_{19}N$: 345.1522.

9-(Diphenylmethylene)-2-methoxy-9*H*-fluorene (12g): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.72 (dd, *J* = 7.52, 3.12 Hz, 2H), 7.35–7.46 (m, 4H), 7.31 (d, *J* = 8.62 Hz, 2H), 7.21–7.28 (m, 3H), 6.90–7.02 (m, 4H), 6.84 (d, *J* = 7.89 Hz, 1H), 6.63 (d, *J* = 8.07 Hz, 1H), 3.88 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.8, 145.5, 143.3, 140.4, 138.9, 135.3, 133.8, 131.5, 130.0 (+), 128.7 (+), 128.2 (+), 127.4 (+), 127.4 (+), 126.3 (+), 126.3 (+), 124.8 (+), 124.7 (+), 119.2 (+), 114.1 (+), 55.3 (+); HR-MS (EI): *m/z* = 360.1514, calcd. for $C_{27}H_{20}O$: 360.1513.

9-{Phenyl[4-(trifluoromethyl)phenyl]methylene}-9*H*-fluorene (12h): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.67–7.76 (m, 3H), 7.53 (d, *J* = 8.07 Hz, 2H), 7.45 (s, 2H), 7.33–7.40 (m, 2H), 7.22–7.31 (m, 3H), 6.89–7.01 (m, 3H), 6.62 (dd, *J* = 7.89, 4.22 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 146.6, 143.2, 142.3, 140.8, 140.6, 138.4, 138.1, 135.2 (+), 130.1 (+), 129.6 (+), 129.1, 128.5 (+), 128.1 (+), 127.2 (+), 126.6 (+), 125.9 (+), 125.0 (+), 124.8 (+), 119.5 (+), 119.4 (+); HR-MS (EI): *m/z* = 398.1282, calcd. for $C_{27}H_{17}F_3$: 398.1285.

9-(Diphenylmethylene)-2-(trifluoromethyl)-9*H*-fluorene (12i): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.67–7.76 (m, 3H), 7.53 (d, *J* = 8.07 Hz, 2H), 7.45 (s, 2H), 7.33–7.40 (m, 2H), 7.22–7.31 (m, 3H), 6.89–7.01 (m, 3H), 6.62 (dd, *J* = 7.89, 4.22 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 147.6, 143.2, 143.6, 141.8, 140.6, 139.0, 138.1, 135.2 (+), 131.1 (+), 129.0 (+), 128.8, 128.5 (+), 128.1 (+), 127.2 (+), 126.6 (+), 125.9 (+), 125.0 (+), 124.9 (+), 120.5 (+), 119.4 (+); HR-MS (EI): *m/z* = 398.1283, calcd. for $C_{27}H_{17}F_3$: 398.1285.

9-[1,3-Difluoro-9-(4-methylphenylphenyl)methylene]-9*H*-fluorene (12k): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.69 (d, *J* = 7.70 Hz, 1H), 7.40–7.50 (m, 1H), 7.30–7.38 (m, 3H), 7.24–7.29 (m, 2H), 7.21 (s, 2H), 7.12 (d, *J* = 6.97 Hz, 2H), 6.99 (s, 1H), 6.58–6.64 (m, 1H), 6.43–6.55 (m, 2H), 2.47 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 148.5, 145.0, 144.1, 143.2, 142.0, 140.7, 140.1, 139.1, 138.6, 138.3 (+), 130.9 (+), 130.7 (+), 129.5 (+), 128.9, 128.7 (+), 128.5 (+), 128.2 (+), 127.8 (+), 127.6 (+), 127.2 (+), 124.2 (+), 119.7 (+), 102.8 (+), 102.6 (+), 102.4 (+), 21.5 (+); HR-MS (EI): *m/z* = 380.1377, calcd. for $C_{27}H_{18}F_2$: 380.1380.

4-[9*H*-Fluoren-9-ylidene(4-trifluoromethyl)phenyl-(methyl)]phenyl methyl ether (12l): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.71 (d, *J* = 7.52 Hz, 2H), 7.67 (d, *J* = 8.07 Hz, 2H), 7.50 (d, *J* = 8.07 Hz, 2H), 7.22–7.31 (m, 4H), 6.91–7.01 (m, 4H), 6.81 (d, *J* = 8.07 Hz, 1H), 6.59 (d, *J* = 7.89 Hz, 1H), 3.88 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.0 , 146.9, 143.2, 140.6, 140.5, 138.6, 138.3, 134.8, 134.6, 131.5 (+), 130.5 (+), 130.3, 127.9 (+), 127.9 (+), 126.5 (+), 126.5 (+), 125.7 (+), 124.8 (+), 124.6 (+), 119.4 (+), 119.3 (+), 114.3 (+), 55.4 (+); HR-MS (EI): *m/z* = 428.1387, calcd. for $C_{28}H_{119}F_3O$: 428.1387.

4-Chloro-9-[phenyl(*p*-tolyl)methylene]-9*H*-fluorene (1j): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.50 (s, 1H), 7.39–7.45 (m, 3H), 7.32–7.38 (m, 2H), 7.18–7.32 (m, 6H), 6.99–7.04 (m, 1H), 6.80–6.89 (m, 1H), 6.67–6.74 (m, 1H), 6.58 (dd, *J* = 7.98, 0.83 Hz, 1H), 2.45 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$): δ = 146.9, 143.2, 141.4, 140.0, 139.2, 139.1, 138.5, 136.6, 133.3, 130.8 (s), 130.8 (s), 129.9 (s), 129.8 (s), 129.6 (s), 129.0 (s), 128.9 (s), 128.5, 128.4 (s), 127.5 (s), 126.7 (s), 126.6 (s), 124.5 (s), 123.4 (s), 123.1 (s), 21.5 (s); HR-MS (EI): *m/z* = 380.1175, calcd. for $C_{27}H_{19}Cl$: 378.1179.

9-[(2-Phenyl)phenylmethylene]-9*H*-fluorene (24): ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.77 (d, *J* = 7.15 Hz, 1H), 7.73 (d, *J* = 7.52 Hz, 1H), 7.47–7.56 (m, 2H), 7.41–7.46 (m, 2H), 7.32 (t, *J* = 7.52 Hz, 1H), 7.21–7.27 (m, 2H), 7.08–7.21 (m, 6H), 7.04 (s, 2H), 6.81–6.92 (m, 3H), 6.62 (d, *J* = 8.07 Hz, 1H), 6.52 (d, *J* = 7.52 Hz, 1H); ^{13}C NMR (126 MHz,

$CDCl_3$): δ = 145.9, 142.1, 141.4, 141.3, 141.2, 140.6, 140.4, 139.0, 138.4, 135.3, 130.7 (s), 130.6 (s), 130.5 (s), 128.9 (s), 128.5 (s), 128.4 (s), 128.2 (s), 127.8 (s), 127.8 (s), 127.6 (s), 127.4 (s), 127.2 (s), 126.9 (s), 126.8 (s), 126.4 (s), 125.1 (s), 124.7 (s), 119.4 (s), 119.2 (s); HR-MS (EI): *m/z* = 406.1722, calcd. for $C_{32}H_{22}$: 406.1718.

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