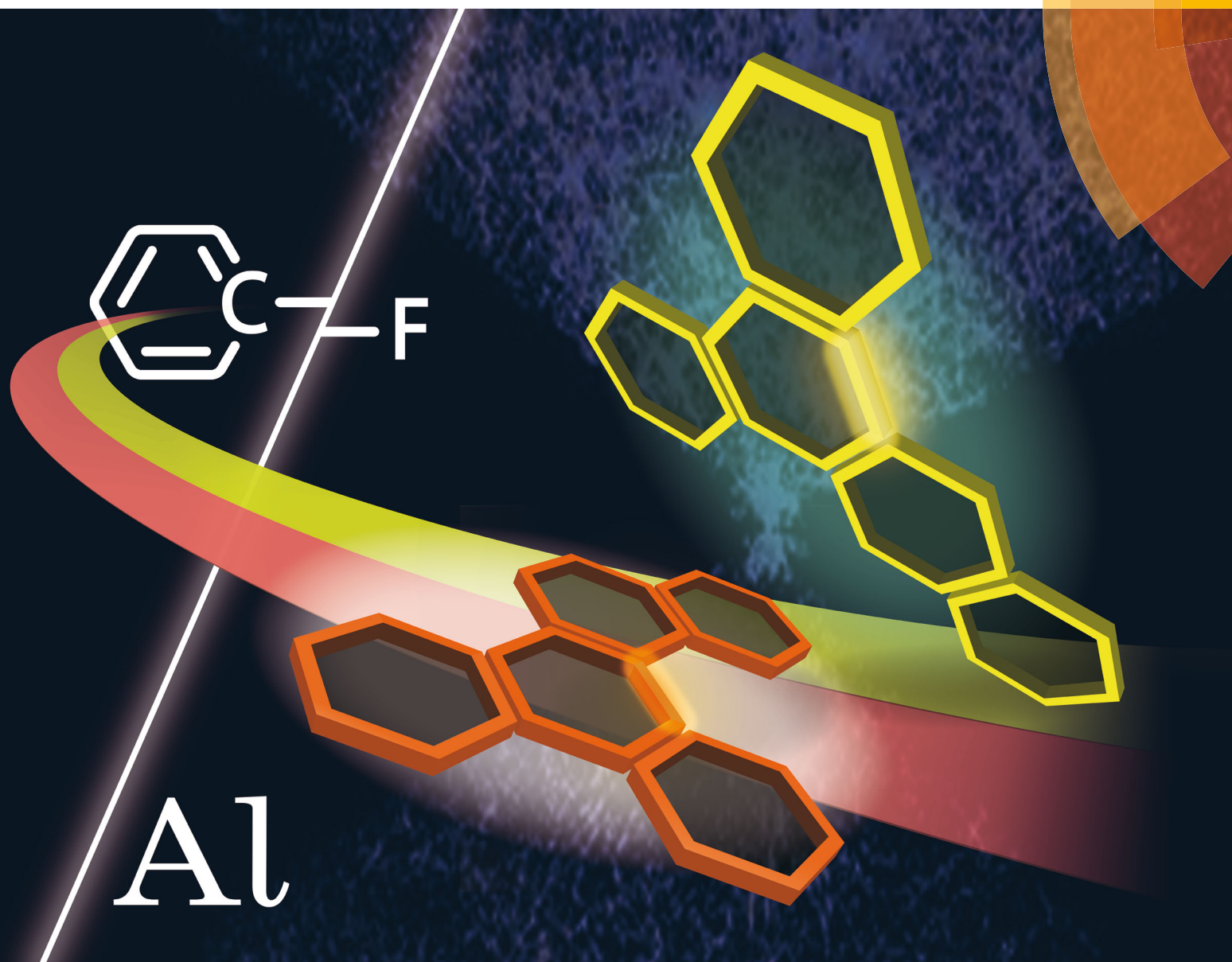


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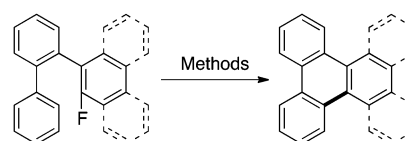
Aluminium-mediated aromatic C–F bond activation: regioswitchable construction of benzene-fused triphenylene frameworks†

Naoto Suzuki,^a Takeshi Fujita,^a Konstantin Yu. Amsharov^b and Junji Ichikawa^{*a}

Selective synthesis of benzo[*f*]tetrapihenes or benzo[*g*]chrysenes was achieved *via* aromatic C–F bond cleavage and unprecedented regioselective C–C bond formation depending upon the choice of aluminium reagents. On treatment with AlCl₃, 2-(biphenyl-2-yl)-1-fluoronaphthalenes afforded exclusively benzo[*f*]tetrapihenes *via* C–C bond formation on the carbon atom γ to the original position of the fluorine substituent. In contrast, α -selective C–C bond formation was promoted by treatment with γ -Al₂O₃ to give benzo[*g*]chrysenes.

Chemical transformations of aromatic carbon–halogen bonds are widely utilised in materials science as well as life science. Among them, reactions involving aromatic carbon–fluorine (C–F) bond cleavage still remain challenging owing to its high bond energy.¹ Activation of aromatic C–F bonds has been conventionally achieved *via* nucleophilic substitution (S_NAr)² or recently *via* transition-metal-catalysed oxidative addition.³ However, the former method is typically limited to electron deficient fluoroarene substrates, while the latter often requires special ligands, directing groups and/or harsh conditions. As new approaches, Siegel and Amsharov independently reported the synthesis of polycyclic aromatic hydrocarbons (PAHs) by cationic cyclisations *via* aromatic C–F bond activation using silylium equivalents (Scheme 1a)⁴ and γ -Al₂O₃ (Scheme 1b),⁵ respectively.⁶ In contrast, Ichikawa accomplished dibenzo[*g,p*]chrysene synthesis *via* the FSO₃H·SbF₅- or TiF₄-promoted double C–F bond activation of 1,1-difluoro-1-alkenes bearing two biaryl groups, where aromatic C–F bond activation was involved in the second cyclisation of intermediary 9-(biaryl-2-yl)-10-fluorophenanthrenes (Scheme 1c).⁷

In the course of our studies on acid-promoted aromatic C–F bond activation,^{7,8} we found that treating 2-(biphenyl-2-yl)-1-fluoronaphthalene (**1a**) with FSO₃H·SbF₅ or TiF₄ selectively



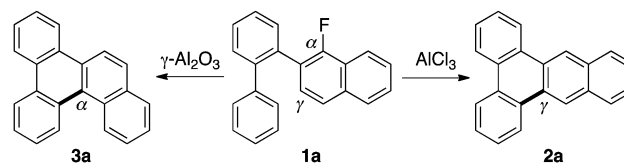
Methods

- (a) Siegel: ArMe₂Si⁺X⁻
(b) Amsharov: γ -Al₂O₃
(c) Ichikawa: FSO₃H·SbF₅ or TiF₄ / (CF₃)₂CHOH

Scheme 1 PAH synthesis by cationic cyclisation *via* aromatic C–F bond activation.

afforded benzo[*f*]tetrapihene (**2a**). In this reaction, fluoro-naphthalene **1a** underwent intramolecular cyclisation *via* C–F bond cleavage and unprecedented regioselective C–C bond formation at the carbon atom γ to the original position of the fluorine substituent.⁹ As a result of acid screening, AlCl₃ was found to be the best acid for this reaction (Scheme 2). Conversely, when **1a** was treated with γ -Al₂O₃, benzo[*g*]chrysene (**3a**) was selectively obtained *via* C–F bond cleavage and C–C bond formation at the α -carbon atom (Scheme 2). Thus, we achieved complete switching of the regioselectivity in defluorinative intramolecular cyclisation of the single substrate **1a** using different aluminium reagents, which led to the synthesis of different benzene-fused triphenylene compounds.^{10,11}

The 2-(biaryl-2-yl)-1-fluoronaphthalene cyclisation precursors **1** were prepared from 1-fluoro-2-iodonaphthalene (**4a**, Scheme 3). 2-(Biphenyl-2-yl)-1-fluoronaphthalene (**1a**) was prepared directly from **4a** *via* the Suzuki–Miyaura coupling with



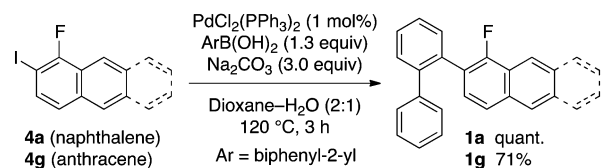
Scheme 2 Regioswitchable synthesis of benzene-fused triphenylenes depending on the aluminium reagent employed.

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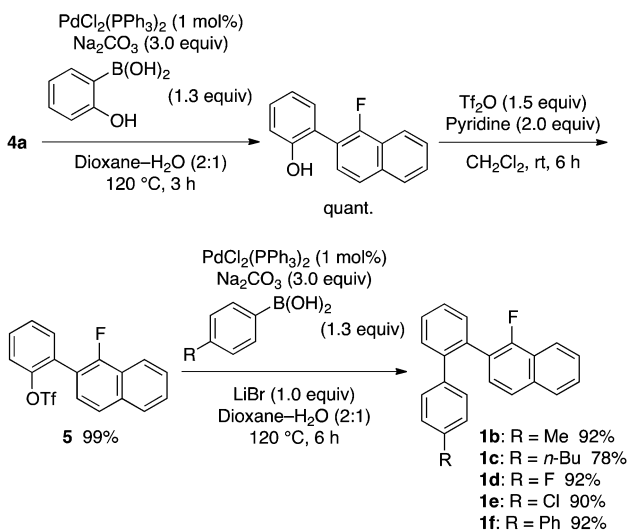
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† Electronic supplementary information (ESI) available: Experimental procedures and characterisation data of new compounds. See DOI: 10.1039/c6cc07199f

(a) Non-substituted precursors



(b) Substituted precursors

Scheme 3 Preparation of cyclisation precursors **1**.

(biphenyl-2-yl)boronic acid in quantitative yield (Scheme 3a). The preparation of ring-substituted precursors involved double Suzuki–Miyaura coupling reactions of **4a** with (2-hydroxyphenyl)boronic acid and of the resulting 2-(1-fluoronaphthalen-2-yl)phenyl trifluoromethanesulfonate (**5**) with 4-substituted phenylboronic acids (Scheme 3b). Thus, methyl-, butyl-, fluoro-, chloro- and phenyl-bearing 2-(biphenyl-2-yl)-1-fluoronaphthalenes **1b–1f** were obtained in high yields. Furthermore, 2-(biphenyl-2-yl)-1-fluoroanthracene (**1g**) was prepared *via* the Suzuki–Miyaura coupling of 1-fluoro-2-iodoanthracene (**4g**) with (biphenyl-2-yl)boronic acid according to the procedure for the preparation of **1a** from **4a** (Scheme 3a).

Upon treatment with FSO₃H·SbF₅ or TiF₄, which were suitable acids for the synthesis of dibenzo[*g,p*]chrysenes from 1,1-difluoro-1-alkenes, in 1,1,1,3,3,3-hexafluoropropan-2-ol (HFIP),^{7,8} 2-(biphenyl-2-yl)-1-fluoronaphthalene (**1a**) selectively afforded benzo[*f*]tetrathene (**2a**) in 12% or 47% yield (Table 1, entries 3 and 4). In these cases along with C–F bond cleavage, C–C bond formation proceeded at the carbon γ to the fluorine substituent instead of at the α carbon. We thus sought suitable conditions for the synthesis of **2a** *via* defluorinative cyclisation of **1a** with a series of Brønsted and Lewis acids (Table 1). While *p*-toluenesulfonic acid (TsOH) gave no cyclised products (entry 1), treating **1a** with 2.5 equiv. of trifluoromethanesulfonic acid (TfOH) selectively afforded **2a** in 97% yield (entry 2). Among the Lewis acids examined (entries 4–10), AlCl₃ and ZrCl₄ effectively promoted the cyclisation of **1a** in HFIP to give **2a** in almost quantitative yields (entries 7 and 10). Screening of

Table 1 Screening of conditions for selective synthesis of benzo[*f*]tetrathene (**2a**)

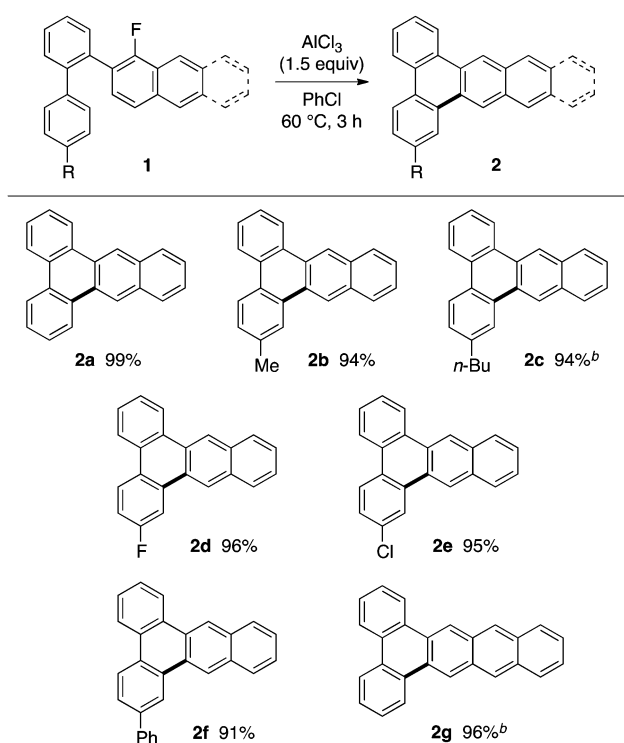
Entry	Acid	Solvent	2a ^a (%)	3a ^a (%)
1	TsOH	(CF ₃) ₂ CHOH	N.D. ^b	N.D. ^b
2	TfOH	(CF ₃) ₂ CHOH	97	< 1
3 ^c	FSO ₃ H·SbF ₅	(CF ₃) ₂ CHOH	12	N.D. ^b
4	TiF ₄	(CF ₃) ₂ CHOH	47	N.D. ^b
5	TiCl ₄	(CF ₃) ₂ CHOH	N.D. ^b	N.D. ^b
6	ZrF ₄	(CF ₃) ₂ CHOH	N.D. ^b	N.D. ^b
7	ZrCl ₄	(CF ₃) ₂ CHOH	99	< 1
8	Me ₃ SiOTf	(CF ₃) ₂ CHOH	52	N.D. ^b
9	BF ₃ ·OEt ₂	(CF ₃) ₂ CHOH	N.D. ^b	N.D. ^b
10	AlCl ₃	(CF ₃) ₂ CHOH	99 (98)	< 1
11	AlCl ₃	PhCl	99	< 1
12	AlCl ₃ ^d	PhCl	99 (99)	< 1

^a Yield was determined by ¹H NMR measurement using CH₂Br₂ as an internal standard. Isolated yield is given in parentheses. ^b N.D. = Not detected. ^c 0 °C, 1 h. ^d AlCl₃ (1.5 equiv.).

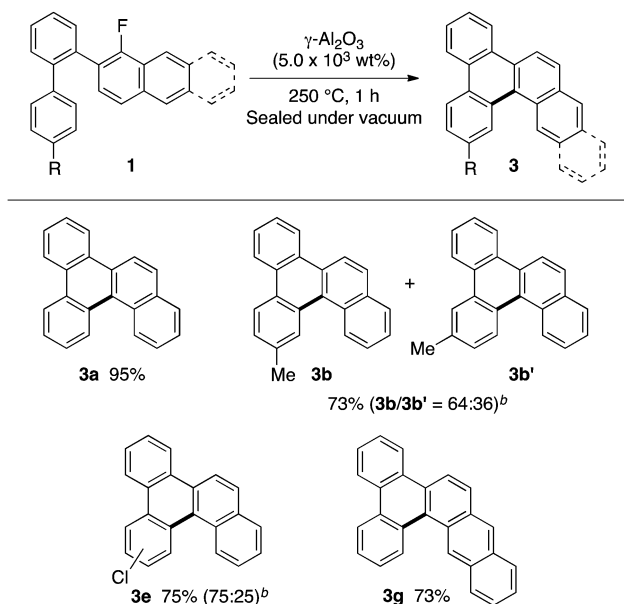
the solvents used with AlCl₃ revealed that chlorobenzene also exhibited a high efficiency comparable to that of HFIP (entry 11). We thus decided to use AlCl₃ as the reagent and chlorobenzene as the solvent for cyclisation of **1a** owing to their low cost. Finally, the reaction still proceeded with quantitative yield when the amount of AlCl₃ was decreased from 2.5 equiv. to 1.5 equiv. (entry 12).

The defluorinative cyclisation of 2-(biaryl-2-yl)-1-fluoronaphthalenes **1** with different substituents was examined using the optimised conditions obtained above for the synthesis of **2a** from **1a** (Table 2). Alkyl-substituted 2-(biphenyl-2-yl)-1-fluoronaphthalenes **1b** and **1c** successfully underwent defluorinative cyclisation to afford the corresponding benzo[*f*]tetrathenes **2b** and **2c** in high yields; however, the effective cyclisation of the butyl-bearing substrate required HFIP as the solvent instead of chlorobenzene. The cyclisation of the fluorinated and chlorinated 2-(biphenyl-2-yl)-1-fluoronaphthalenes **1d** and **1e** proceeded without the loss of the halogen atoms at the 4'-positions. Phenyl-substituted benzo[*f*]tetrathene **2f** was also obtained in 91% yield from 1-fluoronaphthalene **1f** bearing a *p*-terphenyl moiety. The reaction of fluoroanthracene derivative **1g** proceeded in HFIP to afford dibenzo[*a,c*]tetracene (**2g**) in 96% yield.

In contrast to the reactions with AlCl₃, γ -Al₂O₃ promoted defluorinative cyclisation of fluoronaphthalenes **1** at the carbon α to the fluorine substituent (Table 3). Treatment of **1a** with 5.0 × 10³ wt% of γ -Al₂O₃ at 250 °C in a pre-evacuated sealed tube afforded benzo[*g*]chrysene (**3a**) in 95% yield as the sole product. α -Selective cyclisation of methyl- and chlorine-substituted fluoronaphthalenes **1b** and **1e** also proceeded successfully to afford the corresponding benzo[*g*]chrysenes in 73% and 75% yields, respectively. In these reactions, partial migration of the substituents occurred during cyclisations

Table 2 Selective synthesis of benzo[*f*]tetraphenes **2**^a

^a Isolated yield. ^b HFIP was used as the solvent instead of PhCl.

Table 3 Selective Synthesis of Benzo[*g*]chrysenes **3**^a

^a Isolated yield. ^b Regioisomer ratio was determined by ¹H NMR measurement.

probably by *ipso* attack of the biaryl moiety, indicating that the reaction would proceed *via* C–F bond polarization leading to an aryl cation-like intermediate (*vide infra*).¹² Because of the high tolerance of C–F bond activation conditions to aryl C–Cl bonds

Table 4 Effect of halogen substituents

Reaction scheme for Table 4: 2-(biaryl-2-yl)-1-halogenonaphthalene (**1**) reacts with AlCl₃ (1.5 equiv) and PhCl at 60 °C for 3 h to form benzo[*f*]tetraphene (**2a**) and benzo[*c*]tetraphene (**3a**).

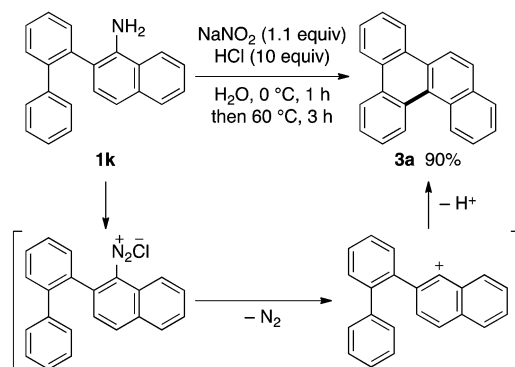
Entry	1	2a ^a (%)	3a ^a (%)
1	1a : X = F	99	< 1
2	1h : X = Cl	73	2
3	1i : X = Br	39	4
4	1j : X = I	22	3

^a Yield was determined by ¹H NMR measurement using CH₂Br₂ as an internal standard.

as shown in Tables 2 and 3, both approaches open a facile way to various chlorinated PAHs, which are less accessible by other methods. Furthermore, dibenzo[*a,c*]tetraphene (**3g**) was produced by the reaction of 2-(biphenyl-2-yl)-1-fluoroanthracene (**1g**) in 73% yield under the same conditions.

In order to gain mechanistic insight into the γ -selective cyclisation of 2-(biaryl-2-yl)-1-fluoronaphthalenes **1**, the effect of the fluorine substituent was investigated by comparing the efficiency of the cyclisation with the corresponding halonaphthalenes (Table 4). When 1-chlorinated, -brominated and -iodinated 2-(biphenyl-2-yl)naphthalenes **1h–j** were subjected to the optimal conditions used for γ -selective cyclisation of fluoro substrate **1a**, all the halides exhibited diminished yields of cyclised product **2a** compared to that of **1a** (entries 2–4 *vs.* entry 1). These results indicate that the high efficiency in γ -selective cyclisation of **1a** can be attributed to the relatively ready generation of the fluorine-stabilised intermediary arenium ions.^{7,13}

In contrast, cyclisation of an aryl cation intermediate generated from a fluorine-free precursor exhibited opposite regioselectivity (Scheme 4). When 2-(biphenyl-2-yl)naphthalene-1-diazonium chloride, prepared from 2-(biphenyl-2-yl)naphthalen-1-amine (**1k**), was heated at 60 °C, benzo[*g*]chrysene (**3a**) was obtained in 90% yield as the sole product.¹⁴ This result suggests that the reaction of 2-(biphenyl-2-yl)-1-fluoronaphthalene (**1a**) with γ -Al₂O₃ might proceed *via* an aryl cation-like intermediate.



Scheme 4 Cyclisation of an aryl cation intermediate.

In summary, we have achieved highly effective cyclisations of 1-fluoronaphthalenes bearing biaryl groups *via* aromatic C–F bond activation mediated by aluminium reagents. It is noteworthy that the choice of aluminium reagents altered the regioselectivities in the cyclisation of common 2-(biaryl-2-yl)-1-fluoronaphthalene precursors, enabling the selective synthesis of two different benzotriphenylenes, *i.e.*, benzo[*f*]tetraphenes and benzo[*g*]chrysenes. Since higher order PAHs are particularly promising constituents in organic electronic devices,¹⁵ the formation of extended π -systems by the current methodology appears to be a powerful route to functional materials.

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