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Direct Arylation of Polycyclic Aromatic Hydrocarbons through Palladium Catalysis

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Supporting Information

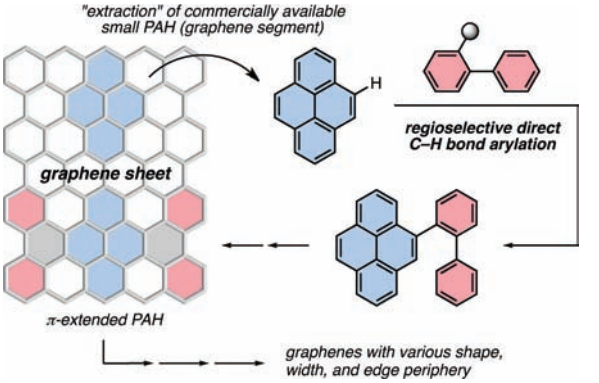
ABSTRACT: We have discovered that the combination of $Pd(OAc)_2$/*o*-chloranil can catalyze the direct C−H bond arylation of polycyclic aromatic hydrocarbons (PAHs) with arylboroxins that occurs selectively at the K-region. The sequential integration of Pd-catalyzed direct arylation of PAHs and $FeCl_3$-mediated cyclodehydrogenation is effective in rapidly extending a parent PAH π-system with high directionality.

Graphenes, two-dimensional sheets of sp^2-hydridized carbon, have received tremendous amounts of interests from almost all areas of science and technology.[1] As the shape, width, and edge periphery (topology) determine the properties of graphenes, a bottom-up synthesis of structurally uniform graphenes is recognized as one of the greatest challenges of primary importance in this research field.[1,2] Among various potential strategies, a two-step approach through (i) controlled organic synthesis of relatively large polycyclic aromatic hydrocarbons (PAHs) with various topologies,[3] followed by (ii) the surface-assisted coupling of these PAHs[4] or (ii′) the amplification sheet-growth using these PAHs as a seed,[5] holds promise for a controlled synthesis of graphenes. As a possible first step toward this end, we herein report the regioselective direct arylation of PAHs with arylboroxins catalyzed by $Pd(OAc)_2$/*o*-chloranil system (Scheme 1). We also demonstrate that the sequential integration of Pd-catalyzed direct arylation of PAHs and $FeCl_3$-mediated cyclodehydrogenation is particularly effective in extending a parent PAH π-system with high directionality.

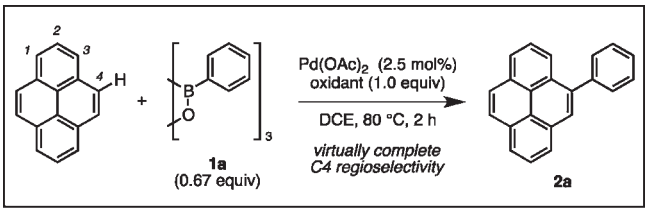
During the last two decades, significant progress has been made in the synthesis of various types of extended PAHs as exemplified by Müllen's giant molecular graphenes and nanoribbons.[3] Typically, these extended PAHs have been fabricated by (i) unit assembly using Diels−Alder reaction[6] or Suzuki−Miyaura coupling[7] followed by (ii) cyclization using cyclodehydrogenation,[8] flash-vacuum pyrolysis,[9] benzannulation,[10] photocyclization,[11] and ring-closing metathesis.[12] In addition to these valuable routes, we envisioned that a direct C−H bond arylation of commercially available small PAHs occurring in a regioselective and predictable fashion should find significant utility in the synthesis of extended PAHs.[13,14]

We began our study by examining various arylating reagents, catalysts, and additives in the C−H bond arylation of pyrene, a model substrate for commercially available PAH. After extensive screening, we identified that the combination of $Pd(OAc)_2$ (catalyst), *o*-chloranil (oxidant), and arylboroxins (arylating reagents) as providing the best system (Scheme 2). For example, pyrene (1.0 equiv) could be effectively phenylated with phenylboroxin

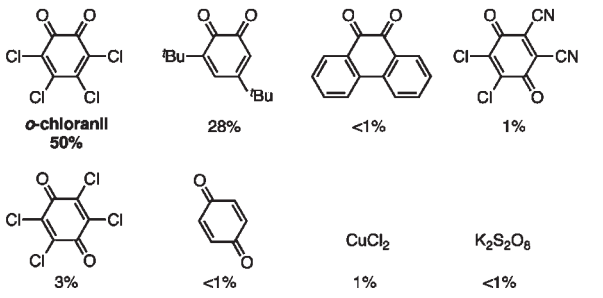
Scheme 1. Direct Arylation of Small PAHs as a Possible Initial Step toward Controlled Synthesis of Graphenes



Scheme 2. Pd-Catalyzed Direct C−H Arylation of Pyrene with Phenylboroxin (1a)[a]



oxidant, GC yield of **2a**



[a] Reaction conditions: pyrene (0.20 mmol), **1a** (0.13 mmol), $Pd(OAc)_2$ (5.0 μmol), oxidant (0.20 mmol), DCE (2 mL), 80 °C, 2 h. Yields of **2a** were determined by GC analysis using *n*-dodecane as an internal standard.

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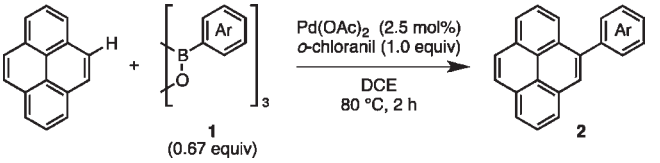
Table 1. C−H Arylation of Pyrene with Arylboroxins 1[a]



1 (0.67 equiv) 2

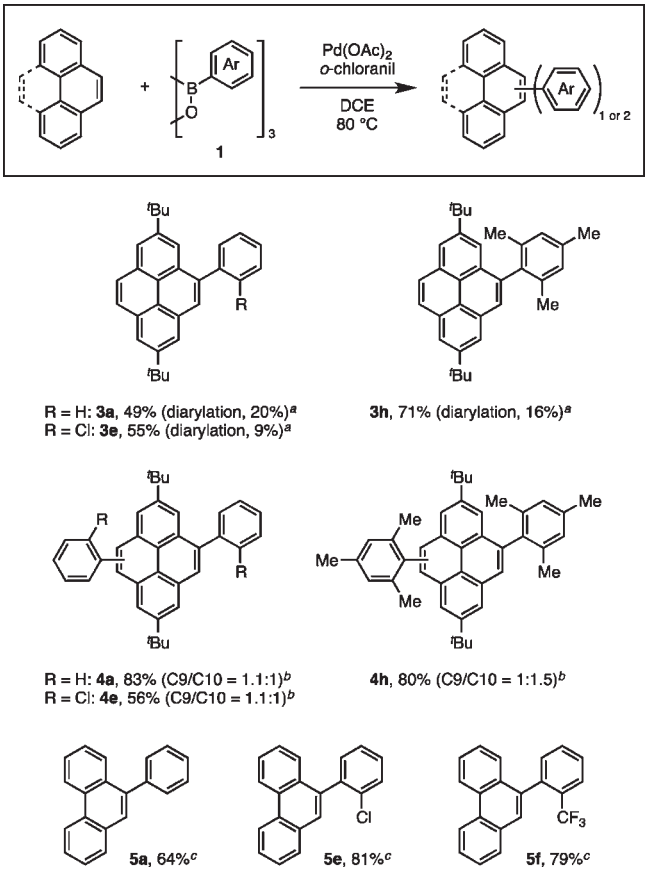
entry	Ar (1)	conversion of pyrene (%)	2	yield (%)[b]
1	1a	69	2a[c]	50 (15)
2	1b	74	2b	49 (7)
3	1c	72	2c	53 (11)
4	1d	68	2d	43 (11)
5	1e	63	2e	52 (8)
6	1f	80	2f	61 (14)
7	1g	77	2g	53 (16)
8	1h	80	2h[c]	54 (8)
9	1i	61	2i	45 (nd)

[a] Conditions: pyrene (0.20 mmol), **1** (0.13 mmol), $Pd(OAc)_2$ (5.0 μmol), *o*-chloranil (0.20 mmol), DCE (2 mL), 80 °C, 2 h. [b] Isolated yields. The numbers in the parentheses are the yields of diarylation products. [c] Structures were confirmed by X-ray crystal structure analysis.

(**1a**: 0.67 equiv) in 1,2-dichloroethane (DCE) at 80 °C under the action of $Pd(OAc)_2$/*o*-chloranil to furnish 4-phenylpyrene (**2a**) in 50% yield after 2 h. Under these conditions, biphenyl (homocoupling product of **1a**) was formed only in 3% yield. Other phenylboron compounds such as phenylboronic acid and the corresponding boronate esters can also be used, albeit in somewhat lower efficiency (see the Supporting Information for details). Very interestingly, the C−H/C−B cross-coupling[15] took place exclusively at the C4 position of the pyrene ring.[16−18]

The use of *o*-chloranil as an oxidant is critically important for the present reaction to occur. As shown in Scheme 2, other frequently used oxidants such as DDQ, *p*-chloranil, *p*-benzoquinone, $CuCl_2$, and $K_2S_2O_8$ were ineffective. 3,5-Di-*tert*-butyl-1,2-benzoquinone was the only oxidant other than *o*-chloranil that displayed any reactivity. It became clear from these studies that the high reactivity of *o*-chloranil stems not only from its high oxidation aptitude,[19] but also from the *o*-quinone structure. Although further investigations are needed, Pd species bound with two oxygen atoms of *o*-chloranil (*o*-quinone, *o*-semiquinone, or catecholate form)[20] might be responsible for the unique reactivity in C−H/C−B coupling.

Scheme 3. Arylation of Substituted Pyrene and Phenanthrene

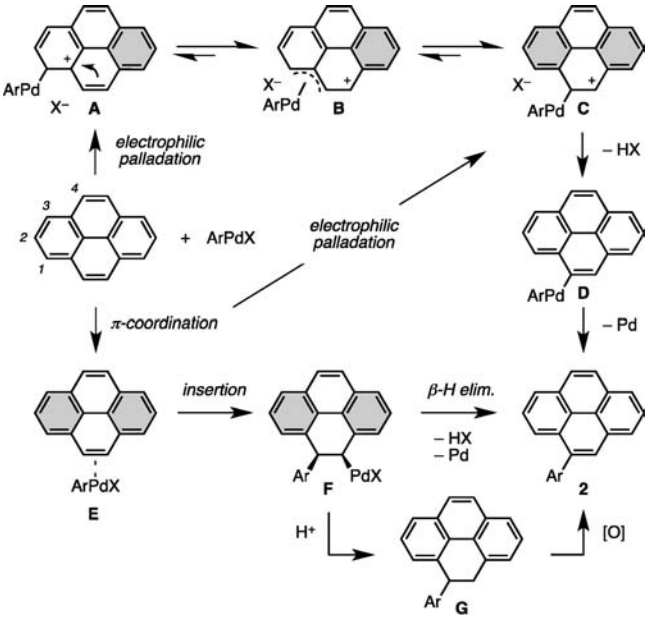


[a] Conditions: 2,7-di-*tert*-butylpyrene (1.0 equiv), arylboroxin (0.67 equiv), $Pd(OAc)_2$ (2.5 mol %), *o*-chloranil (1.0 equiv), DCE, 80 °C, 2 h. [b] Conditions: 2,7-di-*tert*-butylpyrene (1.0 equiv), arylboroxin (1.0 equiv), $Pd(OAc)_2$ (5 mol %), *o*-chloranil (2.0 equiv), DCE, 80 °C, 12 h. [c] Conditions: phenanthrene (1.0 equiv), arylboroxin (0.67 equiv), $Pd(OAc)_2$ (5 mol %), *o*-chloranil (1.5 equiv), DCE, 80 °C, 12 h.

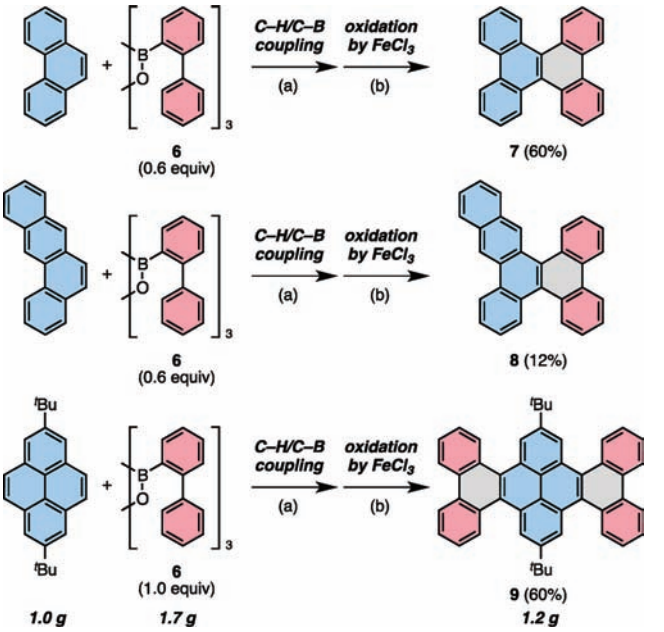
Having developed an efficient $Pd(OAc)_2$/*o*-chloranil catalytic system, we then examined the scope of applicable arylboroxins **1** (Table 1). Under the optimized conditions shown in Scheme 2, various electronically and structurally diverse arylboroxins were found to react with pyrene to give the corresponding 4-arylpyrenes **2** in moderate to good isolated yields. Some of the structures of **2** were unambiguously confirmed by X-ray crystallography (entries 1 and 8). Although diarylation also took place, pyrene was mainly converted to the arylation products; combined yields of mono- and diarylation products based on reacted pyrene were good to excellent. Sterically demanding groups such as *ortho*-substituted phenyl groups, the mesityl group, and the 1-naphtyl group were effectively transferred to the pyrene ring (entries 5−9).

On the basis of these findings, we further investigated the range of PAHs that could be employed. In this study, we report the reactions of PAHs having K-regions (Scheme 3).[21] The reaction of 2,7-di-*tert*-butylpyrene with phenyl-, 2-chlorophenyl-, and mesitylboroxin proceeded smoothly to give the corresponding 4-arylated pyrenes (**3a**, **3e**, and **3h**) in good yields. When 2,7-di-*tert*-butylpyrene was treated with an excess of arylboroxins (**1a**, **1e**, and **1h**), the double C−H arylation took place to afford

Scheme 4. Possible Mechanisms for C4-Selective Arylation of Pyrene



Scheme 5. Synthesis of Extended PAHs through Sequential C−H Arylation with *o*-Biphenylboroxin and $FeCl_3$ Oxidation[a]



[a] Conditions: (a) PAH (1.0 equiv), **6** (0.6 equiv for **7** and **8**, 1.0 equiv for **9**), $Pd(OAc)_2$ (5 mol %), *o*-chloranil (1.2 equiv for **7** and **8**, 2.2 equiv for **9**), DCE, 80 °C. (b) $FeCl_3$ (5.0 equiv for **7** and **8**, 7.5 equiv for **9**), DCM/$MeNO_2$, 0 °C to rt.

the corresponding diaryled pyrenes (**4a**, **4e**, and **4h**) in good to high yields. It was also found that there is almost no regiocontrol over the second arylation (C9/C10 = 1.1:1−1:1.5), although we observed a small aryl group dependence on regioselectivity. The C−H arylation of phenanthrene also occurred efficiently with various arylboroxins to afford the corresponding 9-arylphenanthrenes (**5a**, **5e**, and **5f**) in good to excellent yields.[14] As in the case of pyrene, phenanthrene reacted exclusively at the K-region.

Apart from achieving the efficient π-extension of PAHs through Pd catalysis, the unique regioselectivity (e.g., C4-selectivity for pyrene) is particularly interesting as it might provide insight into the mechanism. Although the precise details are unclear at present, several mechanisms could explain the C4-selectivity of pyrene arylation (Scheme 4). One possible mechanism is based on electrophilic palladation followed by palladium migration. Similar to typical S_EAr reactions,[16] electrophilic palladation of pyrene with arylpalladium species (generated from **1**) might occur at the most nucleophilic C1 position of pyrene ring. This initially formed cationic intermediate **A** can isomerize into the formal C4-attacked intermediate **C** through $\sigma-\pi-\sigma$ isomerization of allylic palladium species **B**. From a consideration of resonance effects, **C** is likely to be thermodynamically more stable than the other possible intermediates as it has two intact benzene rings within the pyrene framework. Deprotonation of **C** followed by reductive elimination from **D** produces 4-arylpyrenes **2**.

Another possible mechanism is based on pyrene−palladium complexation. As indicated in other works,[22] the π-complexation of palladium might occur selectively at the C4−C5 double bond of pyrene (K-region). Electrophilic palladation triggered by this complexation (**E**) would directly furnish the cationic intermediate **C**. Alternatively, Heck-like carbopalladation (insertion) of arylpalladium species might occur from **E** to give **F**. This is reminiscence of the C4-regioselectivity observed in the addition of methyllithium to pyrene.[23] The thus-formed **F** can be transformed to 4-arylpyrenes **2** either by β-hydrogen elimination or by protodepalladation/oxidation sequence. Further detailed study for the elucidation of the reaction mechanism coupled with the acceleration effect of *o*-chloranil is currently underway.

Finally, we examined the synthesis of more extended PAHs by the sequential integration of Pd-catalyzed C−H bond arylation and cyclodehydrogenation (Scholl reaction).[8a] Shown in Scheme 5 are the representative examples using *o*-biphenylboroxin (**6**) as an arylating agent.[24] For example, phenanthrene cross-coupled with **6** under the action of $Pd(OAc)_2$/*o*-chloranil to afford 9-biphenylated phenanthrene. The follow-up treatment with $FeCl_3$ in $CH_2Cl_2/MeNO_2$ at room temperature successfully closed the "fjord region" of the initial coupling product to furnish dibenzochrysene (**7**) in 60% overall yield. Similarly, the two-step reaction of benzo[*a*]anthracene resulted in the formation of tribenzotetraphene (**8**) in 12% yield. The low isolated yield of **8** is partly due to the solubility issues. Two-directional π-extension of PAHs is even more interesting. For example, a double C−H bond arylation of 2,7-di-*tert*-butylpyrene with **6**, followed by cyclodehydrogenation, gave hexabenzotetracene **9** in 60% yield. It is noteworthy that the reaction can be conducted on a gram scale.

In summary, we have demonstrated that the newly developed $Pd(OAc)_2$/*o*-chloranil system is an effective catalyst for the oxidative direct arylation of PAHs with arylboroxins. The unexpected emergence of unique C4-regioselecivity for pyrene arylation is particularly interesting not only because it provides information about the mechanism, but also because it can be utilized complementarily with the other π-extendable reactions such as bromination (C1)[16] and Ir-catalyzed C−H borylation (C2).[17] We also demonstrate that the sequential integration of Pd-catalyzed direct arylation of PAHs and $FeCl_3$-mediated cyclodehydrogenation is particularly effective in rapidly extending a parent PAH π-system with high directionality. Elucidation of the

mechanism of $Pd(OAc)_2$/*o*-chloranil-mediated C−H bond arylation, synthesis of a whole range of extended PAHs, and the controlled synthesis of graphenes such as graphene nanoribbons are currently ongoing in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedures, characterization data of new compounds, and CIF file of **2a**, **2h**, and **8**. This material is available free of charge via the Internet at http://pubs.acs.org.

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