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Pushing the Ir-Catalyzed C−H Polyborylation of Aromatic Compounds to Maximum Capacity by Exploiting Reversibility

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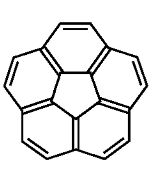
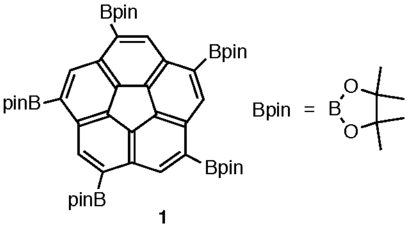
Supporting Information

ABSTRACT: Small amounts of base (e.g., 10% potassium *t*-butoxide or sodium methoxide) have been found to promote equilibration of the kinetically favored products from Ir-catalyzed C−H polyborylations of aromatic compounds. In the presence of excess borylating agent, bis(pinacolato)diborane (B_2pin_2), repetitive deborylation/reborylations reposition the Bpin substituents until a pattern that accommodates the maximum number of Bpin substituents is achieved. A high-yield, one-step synthesis of 1,3,5,7,9-pentakis(Bpin)corannulene is reported that illustrates this useful extension of the Ir-catalyzed borylation reaction.

Boronic acids and their derivatives have rapidly risen to a position of preeminence as versatile synthetic precursors to a wide range of functionalized and C−C coupled arenes.[1] It is only natural, therefore, that the direct borylation of aromatic compounds by Ir-catalyzed C−H activation at unsubstituted sites has drawn considerable attention.[2] For several projects in our own research on geodesic polyarenes, we foresee numerous potential uses for 1,3,5,7,9-pentakis(Bpin)corannulene (**1**).[3−5] Herein we report the gratifying results of our investigations on the direct borylation of corannulene.[6]



corannulene



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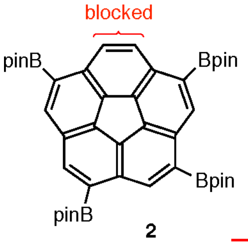
Under standard conditions,[7] the direct borylation of corannulene with B_2pin_2, catalyzed by $[Ir(OMe)COD]_2$ in the presence of various bipyridyl ligands, does indeed produce 1,3,5,7,9-pentakis(Bpin)corannulene (**1**), albeit always as a mixture with the two tetrakis(Bpin)corannulenes **2** and **3**, in a **1**/**2**/**3** ratio of approximately 1:3:1. As expected, the large steric demand of each Bpin substituent precludes borylation not only in the *ortho* position on the same ring but also in the *peri* position on the adjacent ring.[7] The *peri*-Bpin substituents that flank the fifth rings in compounds **2** and **3** block both C−H sites in those rings, so the reactions that lead to these undesired products (multiple pathways) all stop after the fourth borylation. The only other substitution pattern that accommodates four Bpin groups on corannulene without violating the *ortho*/*peri*-prohibition is the one embodied in the 1,3,5,7-isomer (**4**). This isomer never accumulates to any significant extent, because it borylates easily at the one remaining open position under the reaction conditions to yield the desired 1,3,5,7,9-pentakis(Bpin)corannulene (**1**).



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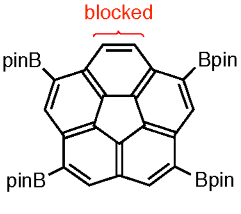

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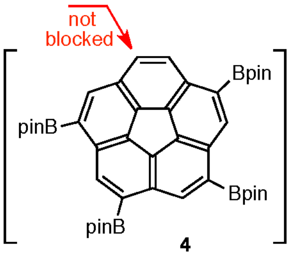

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The low yield of **1** obtained from these experiments impelled us to tinker with the reaction conditions, in an effort to increase the relative amount of **1** produced. Our efforts were rewarded by the discovery of conditions that yield **1** virtually quantitatively, producing almost none of the two tetrakis(Bpin)corannulenes **2** and **3**. A comparison of the ^1H NMR spectrum of the crude product mixture obtained under standard reaction conditions (Figure 1 top) with that of the crude product mixture obtained under these modified reaction conditions (Figure 1 bottom) dramatically underscores the success of our new borylation procedure.

The polyborylation of corannulene can be driven essentially completely to **1** by running the reaction at high concentration with excess B_2pin_2 and a catalytic amount of base (e.g., 10% potassium *t*-butoxide or sodium methoxide) for 4 days in THF at 85 °C in a pressure vessel, along with a high loading (20%) of the standard $[Ir(OMe)COD]_2$ catalyst in a 1:2 molar ratio with 4,4′-dimethylbipyridyl (see the Supporting Information for details). The reaction is slow but reliable.

Monitoring the reaction verifies that a mixture of **1**, **2**, and **3** is formed relatively rapidly in the first day and that the concentration of the pentasubstituted product (**1**) then slowly

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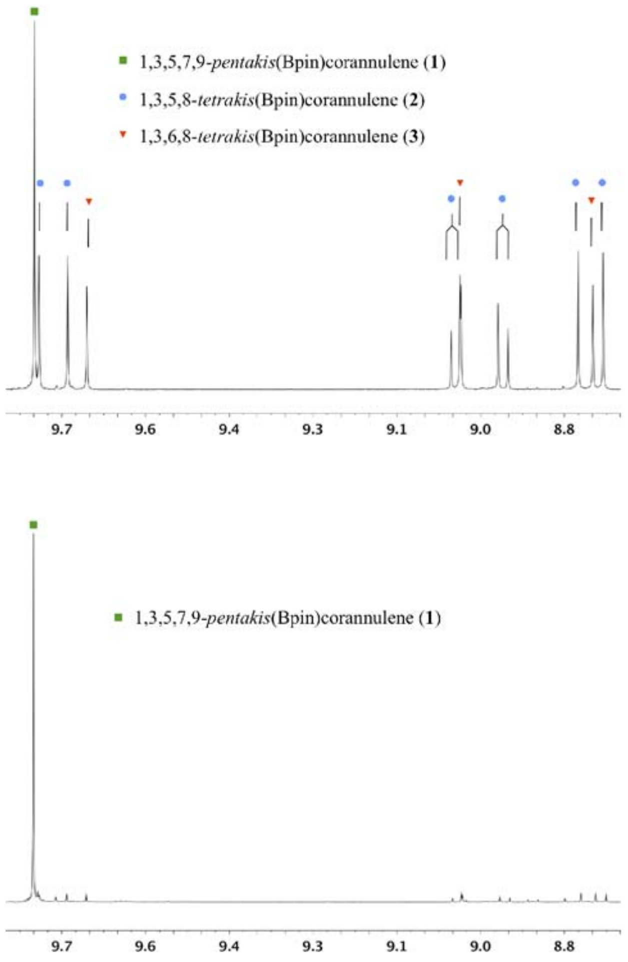


Figure 1. ^{1}H NMR spectra (500 MHz, C_6D_6) of the crude product mixtures obtained from the Ir-catalyzed polyborylation of corannulene. Top: under standard conditions. Bottom: under new conditions. The signals for hydrogens flanked by both an *ortho-* and a *peri*-Bpin neighbor appear in the 9.65−9.75 ppm range. The signals for hydrogens flanked by only one Bpin neighbor, either *ortho-* or *peri-*, appear in the 8.75−9.05 ppm range.

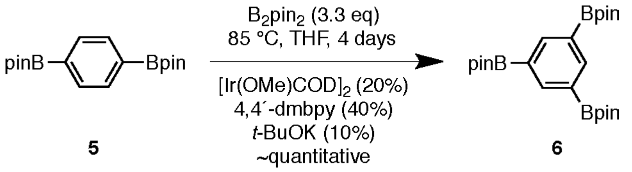


Figure 2. The complete conversion of 1,4-bis(Bpin)benzene (5) to 1,3,5-tris(Bpin)benzene (6) under our new borylation conditions clearly confirms the operation of a deborylation/reborylation "self-correction" process that repositions the Bpin substituents until a pattern that accommodates the maximum number of Bpin substituents is achieved.

rises at the expense of the two tetrasubstituted products (**2** and **3**). Thus, the success of these new polyborylation conditions clearly is *not* a consequence of altered kinetics that favor preferential formation of **1** but depends instead on the operation of some slower substituent redistribution process. This redistribution process does not go to completion if the reaction is run for fewer than 4 days or at significantly lower concentrations, lower temperatures, or lower catalyst loadings. Catalytic amounts of base are not part of the standard conditions for arene borylations but play a critical role in this new procedure. Even Cs_2CO_3, K_2CO_3, and CsF can be used as the base in this reaction. A screening of ligands revealed that 4,4′-dimethylbipyridyl is superior to the normal 4,4′-di-*t*-butylbipyridyl, for reasons that are not immediately apparent to us.[8] Further optimization would likely uncover conditions that allow lower catalyst loadings, but this is no longer our highest priority.

The majority of the 1,3,5,7,9-pentakis(Bpin)corannulene (**1**) can be isolated in analytically pure form simply by precipitating it from the reaction mixture with methanol. The remaining B_2pin_2, catalyst, ligand, base, and byproducts all remain in the filtrate. Rather than trying to separate the remaining **1** from this mixture chromatographically, which is not trivial, we have found it convenient simply to concentrate the filtrate to dryness and heat the residue with acetic acid and HCl to deborylate any **2** or **3** that had formed, along with the remaining **1**, back to corannulene, which can easily be isolated and recycled. From this very simple workup, hardly any corannulene is lost that is not converted to pure **1**.

No more than five Bpin substituents can be accommodated on corannulene without violating the *ortho*/*peri*-prohibition, and this level of substitution can be achieved only in the 1,3,5,7,9-isomer (**1**). Thus, 1,3,5,7,9-pentakis(Bpin)-corannulene (**1**) can be considered "saturated" with Bpin substituents; by the new procedure, the polyborylation has been pushed all the way to the maximum capacity of the corannulene. The buildup and subsequent disappearance of the "wrong" tetrakis(Bpin)corannulenes **2** and **3** clearly indicates that *these new conditions provide a kinetically accessible pathway for deborylation* of these isomers back temporarily to the tris(Bpin)corannulene stage, thus, imparting a self-correction aspect to the synthesis of **1**.[9] A net rearrangement of **2** or **3** to isomer **4** puts the compound on the pathway to **1**. Only one Bpin group must be moved to isomerize **2** into **4**. Isomer **3** must rearrange first to **2** to be transformed into **4**.

To demonstrate this deborylation/reborylation unambiguously in a simpler system, we exposed 1,4-bis(Bpin)benzene (**5**) to our new borylation conditions and observed its complete conversion to 1,3,5-tris(Bpin)benzene (**6**) over a period of 4 days (Figure 2). In light of this result, it is not surprising that the direct borylation of benzene likewise proceeds all the way to 1,3,5-tris(Bpin)benzene (**6**) under these conditions.

To learn more about this new "exhaustive borylation" method, we have examined biphenyl and have found that it behaves in exactly the same manner as corannulene. Thus, borylation of biphenyl under standard conditions produces a complicated mixture of di-, tri-, and tetraborylated derivatives (see the Supporting Information). Under our exhaustive borylation conditions, on the other hand, all of these products are efficiently converted to 3,5,3′,5′-tetrakis(Bpin)biphenyl (**7**, Figure 3). The majority of the product can be isolated in pure form simply by precipitation with methanol (87% isolated yield). Symmetrical polyborylated aromatic hydrocarbons such as **1**, **6**, and **7** represent attractive platforms from which to build dendrimers and other potentially useful materials.

The geodesic curvature of corannulene expands the exocyclic CCC bond angle at each of the five quaternary carbon atoms on the rim to nearly 130°, and this widening reduces the steric repulsion from the *peri*-hydrogen atoms enough for the molecule to accommodate Bpin groups adjacent to every ring junction. In planar polycyclic aromatic hydrocarbons, the corresponding exocyclic CCC bond angles are smaller

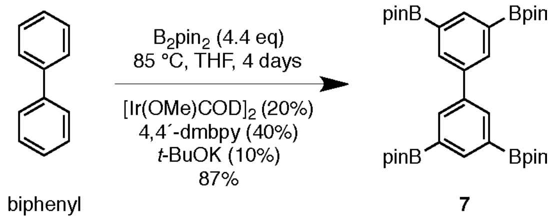


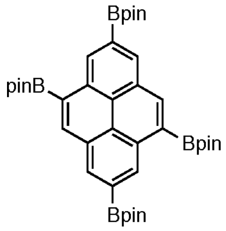
Figure 3. The complicated mixture of di-, tri-, and tetraborylated biphenyls formed under standard borylation conditions can be efficiently converted to 3,5,3′,5′-tetrakis(Bpin)biphenyl (**7**) in high yield.

(~120°), and the cumulative effects of multiple steric repulsions from *peri*-hydrogen atoms makes it more difficult to accommodate Bpin groups adjacent to every ring junction. The borylation of pyrene, for example, can be pushed to 2,4,7,9-tetrakis(Bpin)pyrene (**8**), which has Bpin groups adjacent to two ring junctions, but we have been unable to obtain 1,3,5,7,9-pentakis(Bpin)pyrene (**9**), which would put Bpin groups adjacent to all four ring junctions.[10,11] The surprising absence of the 2,4,7,10-tetrakis(Bpin)pyrene (**10**), an isomer of **8** that also has Bpin groups adjacent to only two ring junctions, reflects the greater strain in the latter isomer.[11] The 1,3,6,8-isomer of tetrakis(Bpin)pyrene (**11**) would have Bpin groups adjacent to four of the ring junctions and is predicted to be even more strained;[11] that isomer is not seen, either. The deborylation/reborylation process eventually puts four Bpin groups on every molecule and ultimately funnels all the tetrakis(Bpin)pyrenes to the most stable isomer, **8**.

Coronene is another challenging polycyclic aromatic hydrocarbon with 120° exocyclic CCC bond angles. Borylation of coronene under standard conditions produces a complicated mixture of Bpin-substituted coronenes with varying numbers of Bpin groups attached, together with unsubstituted coronene. Under our equilibrating conditions with excess B_2pin_2, however, a significant fraction of the material gets converted to the 1,4,7,10-isomer of tetrakis(Bpin)coronene (**12**), which can be isolated pure by precipitation with methanol, albeit only in 10−20% yield. Mass spectrometry confirms the formation also of pentakis- and hexakis(Bpin)coronenes. Chromatography yields a fraction enriched in the symmetrical 1,3,5,7,9,11-hexakis(Bpin)coronene (**13**), which gives rise to a tall singlet at 10.26 ppm in the ^1H NMR spectrum (see the Supporting Information for details).

Catalysts facilitate reactions not only in the forward direction (e.g., borylation) but, inescapably, also in the reverse direction. In principle, therefore, all arene borylations should eventually lead to exhaustive borylation, even under the normal borylation conditions, without base, if they are run long enough with an excess of borylating agent (Le Châtlier's principle). The more exothermic the forward reaction, of course, the slower will be the reverse reaction. What we have found is that catalytic amounts of base accelerate the deborylation of arenes under the borylation conditions, thus, making it feasible to achieve maximum capacity in a finite time frame.

It is tempting to speculate that the base adds to a Bpin substituent, thereby activating it for transmetalation,[12] but we have no experimental evidence for this mechanistic hypothesis. We do know that 1,4-bis(Bpin)benzene (**5**) does not suffer deborylation in the absence of $[Ir(OMe)COD]_2$, when heated for 4 days at 85 °C in THF with 4,4′-dimethylbipyridyl and potassium *t*-butoxide. The iridium catalyst is required for the deborylation.



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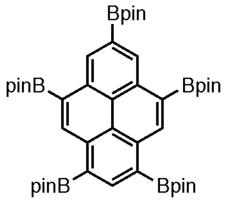

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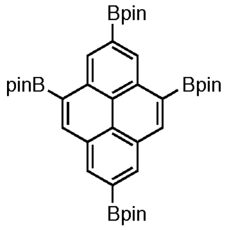

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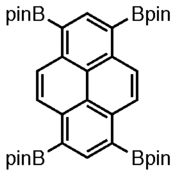

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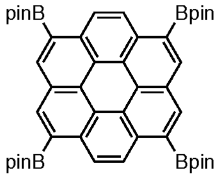

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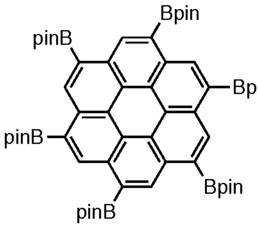

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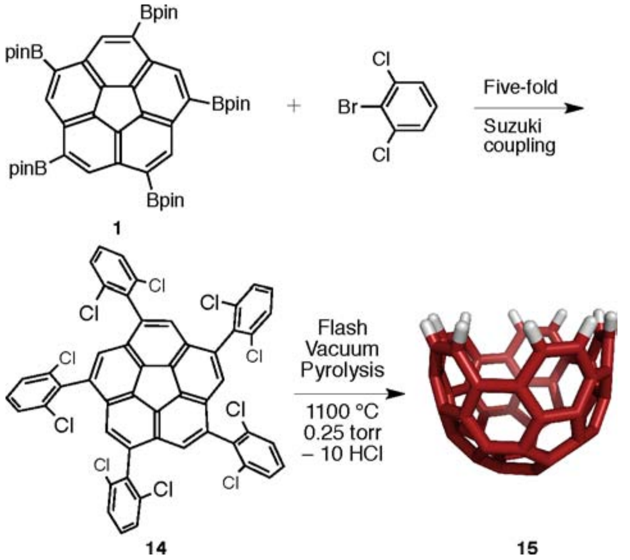

Figure 4. Conversion of **1** to **14**, the precursor used for the first chemical synthesis of a short, isomerically pure [5,5]nanotube (**15**). Suzuki conditions: $Pd(dppf)Cl_2$, Cs_2CO_3, THF, 95 °C, 50−70% yield (87−93% for each C−C bond-forming step).

We have begun using 1,3,5,7,9-pentakis(Bpin)corannulene (**1**) for a variety of purposes. A 5-fold Suzuki coupling with 2-bromo-1,3-dichlorobenzene, for example, provides an improved route to 1,3,5,7,9-pentakis(2,6-dichlorophenyl)corannulene (**14**), the precursor from which we have recently synthesized a short, isomerically pure [5,5]nanotube (**15**) by a "bottom up" approach (Figure 4).[13] The isolated yield of **14** from **1** is 50−70% (average from multiple experiments), which corresponds to 87−93% for each Suzuki coupling reaction.[14]

We hope that others will find additional uses for this new method to push the Ir-catalyzed C−H polyborylation of aromatic compounds to maximum capacity.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Spectra, combustion analysis, and experimental procedures for the synthesis, isolation, and purification of **1**; information about the effects of varying the solvent, temperature, time, ligand, base, borylating agent, concentration, and stoichiometry; procedures for the recovery of corannulene from mixtures of borylated corannulene (deborylation); details for the reaction in Figure 2 and for the direct borylation of benzene, biphenyl, pyrene, and coronene; spectra for new polyborylated hydrocarbons **7**, **8**, **12**, and **13**; details for the Suzuki coupling reaction in Figure 4; XYZ coordinates and energies from calculations on the isomeric tetrakis(Bpin)pyrenes **8**, **10**, and **11**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(3) The name 1,3,5,7,9-pentakis(Bpin)corannulene is a shorthand name for 1,3,5,7,9-pentakis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)corannulene.

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(8) This intriguing point is discussed further in the Supporting Information.

(9) The same self-correction principle presumably operates also in the *t*-butylation of corannulene, which gives 1,3,5,7,9-penta-*t*-butylcorannulene; the Friedel-Crafts alkylation is reversible: Sevryugina, Y.; Rogachev, A. Y.; Jackson, E. A.; Scott, L. T.; Petrukhina, M. A. *J. Org. Chem.* **2006**, *71*, 6615.

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