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Journal
Angewandte Chemie International Edition, 56(17)

ISSN
1433-7851

Authors
Kiel, Gavin R
Ziegler, Micah S
Tilley, T Don

Publication Date
2017-04-18

DOI
10.1002/anie.201700818

Peer reviewed

HHS Public Access

Author manuscript

Angew Chem Int Ed Engl. Author manuscript; available in PMC 2018 April 18.

Published in final edited form as:

Angew Chem Int Ed Engl. 2017 April 18; 56(17): 4839–4844. doi:10.1002/anie.201700818.

Zirconacyclopentadiene-Annulated Polycyclic Aromatic Hydrocarbons (ZrPAHs)

Gavin R. Kiel, **Micah S. Ziegler**, and **Prof. T. Don Tilley**

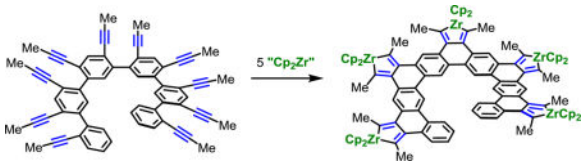
Department of Chemistry, University of California, Berkeley, CA, 94720 (USA)

Abstract

Syntheses of large polycyclic aromatic hydrocarbons (PAHs) and graphene nanostructures demand methods capable of selectively and efficiently fusing large numbers of aromatic rings, yet such methods remain scarce. Here we report a new approach, based on the quantitative intramolecular reductive cyclization of an oligo(diyne) with a low-valent zirconocene reagent, which gives a PAH with one or more annulated zirconacyclopentadienes (ZrPAH). The efficiency is demonstrated by a high-yielding, five-fold intramolecular coupling to form a helical, sixteen-fused-ring ZrPAH (from a precursor with no fused rings). Several other PAH topologies are also reported. Protiodemetallation of the ZrPAHs allowed full characterization (including by X-ray crystallography) of PAHs containing one or more appended dienes possessing the o-quinodimethane (o-QDM) structure, which are usually too reactive to isolate and are potentially valuable for fusion of more rings via Diels-Alder reactions.

TOC Graphic

Zipping up alkynes with zirconocene: a highly-efficient, five-fold reductive cyclization demonstrates the promise of a new strategy for construction of graphene nanostructures. Protiodemetallation of the resulting zirconacyclopentadiene-annulated polycyclic aromatic hydrocarbons (ZrPAHs) provides a conceptually unique means to generate valuable *o*-quinodimethane (*o*-QDM) functionality.



Keywords

quinodimethanes; metallacycles; polycyclic aromatic hydrocarbons; zirconocene coupling; graphene nanostructures

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The isolation of graphene and the elucidation of its extraordinary properties (e.g., ballistic charge transport, mechanical strength, transparency, and flexibility) have motivated a surge of research on large polycyclic aromatic hydrocarbons (PAHs), which can be considered

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Correspondence to: T. Don Tilley.

basic building blocks of graphene and other carbon-rich nanostructures.[1,2] Thus, significant attention has focused on PAHs as molecular models for, or synthetic precursors to, this promising class of materials.[3–5] Large PAHs are also attractive as components of electronic and optoelectronic devices.[6–9] Their suitability for this purpose is due not only to their unique electronic and photophysical properties,[10] which result from their extended conjugation and rigidity, but also their tendency to assemble into highly ordered structures in the solid state.[11]

A central challenge for investigations of large PAHs is the difficulty in syntheses of pure, well-defined structures, which requires the selective fusion of many aromatic rings.[12] Near quantitative yields are necessary for each ring-fusion event to avoid difficult separations and/or defects. To date, the most successful approach is based on the cyclodehydrogenation reaction popularized by Müllen and coworkers, but there are significant limitations with respect to regioselectivity and functional group tolerance.[4,13] Given the ability of transition metals to facilitate selective and high-yielding transformations, they provide a promising platform for the challenging ring-fusion step. Although the development of organometallic methods (e.g., ring-closing alkene metathesis[14] and [2+2+2] cycloadditions[15,16]) has received much attention,[17] few are efficient enough for application to very large PAHs.

We have previously reported the synthesis of π-conjugated oligomers,[18] polymers,[19] and macrocycles[20] *via* the reductive coupling of alkynes with a low-valent zirconocene reagent. Given its ability to form new rings in high yield, this reaction should be well-suited for PAH syntheses. The Takahashi group demonstrated its application to the iterative elongation of an acene (Scheme 1a); however, the strategy is lengthy and requires a post-ring-fusion oxidation step.[21] Wang *et al.* employed zirconacyclopentadienes in the annulation of naphthalene diimides, but alkyne coupling was not involved in the ring fusion event (Scheme 1b).[22] A related and potentially far-reaching approach was indicated more than 40 years ago by Müller,[23] who used diynes with π-conjugated tethers to access several fully-unsaturated fused-ring systems *via* a rhodacyclopentadiene synthon (e.g., **A**, Scheme 1c). Two promising features of this chemistry are: 1) a PAH is *directly* obtained from the precursor (e.g., no subsequent oxidation is required) and 2) functionality can be divergently introduced using metal transfer reactions. Surprisingly, this approach has been employed for only a limited number of PAHs *via* an organometallic intermediate containing a single annulated metallacyclopentadiene.[24,25]

Here we report a generalization of Müller's approach, enabled by the high efficiency of zirconocene coupling. Specifically, the quantitative intramolecular reductive cyclization of an oligo(diyne) (**B**, Scheme 2a) with a low-valent zirconocene reagent gives a zirconacyclopentadiene-annulated PAH ("ZrPAH", **1**). Eleven ZrPAHs (**1a–k**, Scheme 2b), representing seven different PAH topologies, are presented, including one with *sixteen* fused rings and five appended zirconacyclopentadiene rings (**1k**). Importantly, these ZrPAHs result from precursors that have no fused rings and could thus be easily assembled using established C–C bond forming reactions. Furthermore, the high yielding and stereoselective protiodemetallation of **1a–k** was exploited as a novel entry to several PAHs with exocyclic diene functionality (**2a–k**). Such compounds might be expected to exhibit high reactivity, as is typically the case for dienes with the *o*-quinodimethane (*o*-QDM, Figure 1) structure.[26]

However, they are remarkably stable when incorporated into a PAH framework (with certain R substituents), which allowed the isolation and full characterization of eight rare examples (**2a–c** and **2g–k**). Not only are these isolable *o*-QDMs interesting from a fundamental perspective, they also can be selectively hydrogenated using a simple procedure to produce highly alkylated PAHs.

Investigations began with the model system of Scheme 3, which involves the reductive coupling of a diyne (**3–7**) to form a phenanthrene annulated with a single zirconacyclopentadiene (ZrPAHs **1a–e**). There were two initial goals: 1) establish efficient conditions for the zirconocene coupling, which needs to be very high-yielding to be applied in multifold coupling reactions, and 2) determine the suitability of these ZrPAHs as precursors to *o*-QDMs, which might then be employed in Diels-Alder reactions for fusion of additional rings. Toward this end, ZrPAH **1a** was isolated in 92% yield by treatment of diyne **3** with 1.1 equiv of $Cp_2Zr(pyr)(Me_3SiC{\equiv}CSiMe_3)$,[27] a convenient, well-defined source of "Cp_2Zr".[28] Monitoring by ^1H NMR spectroscopy revealed that this reaction is rapid (complete in <5 min) and quantitative.

Treatment of **1a** with excess HCl (5 equiv) produced a surprisingly persistent species consistent with **2a** (as judged by a characteristic quartet at 5.7 ppm and corresponding doublet at 1.8 ppm for the vinyl and methyl protons, respectively) in nearly quantitative yield. Observation of this species despite the presence of excess strong acid is remarkable; however, 70% of **2a** decomposed to an unidentified product within 6 h. Replacement of HCl with benzoic acid produced **2a** in similarly high yield, and there were no signs of its decomposition after one week in benzene-d_6 solution.

The stability of **2a** in solution motivated its isolation, as examples of isolable *o*-QDMs are very rare and invariably involve substitution patterns that preclude their use as synthetic intermediates.[29,30] Treatment of **1a** with excess benzoic acid afforded pure **2a** as a colorless crystalline solid after a simple filtration of the hexanes-diluted reaction mixture through a plug of silica gel. The stability of **2a** permitted its full characterization, including by X-ray crystallography, which revealed its "twisted" nature in the solid state (Figure 2a). This twist can be quantified by two angles: 1) the torsion angle of the exocyclic diene unit (51.3°) and 2) the twist angle of the biphenyl backbone (19.8°). Compound **2a** can be handled for a few hours in air (in solution or as a solid) without detectable decomposition, but prolonged exposure to air at ambient temperature (ca. 21 °C) leads to slow decomposition, probably by oligomerization catalyzed by O_2. The solid can be stored indefinitely under nitrogen at ambient temperature. In the absence of O_2, ring-closure to cyclobutarene **8** (Scheme 3) is the major decomposition pathway, but heating to 100 °C for 24 h was required for complete conversion. In contrast, the unsubstituted analogue **9** could not be isolated and was reported to rapidly decompose *via* [4+2] dimerization.[31]

The analogous n-propyl-substituted *o*-QDM **2b** was prepared in 95% yield by *in situ* generation of **1b** using Negishi's $Cp_2ZrCl_2/^nBuLi$ reagent,[32] followed by treatment with aqueous HCl. This high yield was possible despite the use of excess strong acid, but short reaction times (<10 min) are required. Successful isolation of $SiMe_3$-substituted *o*-QDM **2c** required stoichiometric HCl, as this compound rapidly reacted with excess HCl to form an

unidentified product. Employment of benzoic acid gave a mixture containing only a small amount of **2c** (~10%).

An attempt to isolate diaryl-substituted *o*-QDM **2d** led, instead, to cyclobutarene **10** as the sole product upon protiodemetallation of **1d** with HCl, likely through electrocyclic ring-closing of **2d**. Treatment with benzoic acid gave a complex mixture. An intermediate case was mono-aryl-substituted *o*-QDM **2e**, which cyclized to **11** with a half-life of ~2 days at 19 °C upon protiodemetallation of **1e** with HCl. The intermediate **2e** was identified by ^{1}H NMR spectroscopy in 93% yield. It is well known that aryl groups lower the barrier for this reversible ring-closing reaction.[33]

Thiophene-annulated *o*-QDM **2f** (Scheme 4) was predicted to be more reactive than its benzannulated analogue **2a** for two reasons: 1) a diminished steric interaction between the methyl groups and annulated rings and 2) lower aromaticity of the annulated thiophene rings. Indeed, generation of ZrPAH **1f** from diyne **12** followed by its *in situ* protiodemetallation led to a rapid (< 5 min) 1,4-addition of HCl to yield **13** as the major product. The intermediacy of **2f** is supported by the isolation of Diels-Alder adduct **14** in 76% yield (in one pot, from **12**) upon protiodemetallation in the presence of *N*-ethylmaleimide at 21 °C. In contrast, the analogous Diels-Alder reaction with **2a** (Scheme 4) required elevated temperature to proceed at a reasonable rate (70 °C for 15 h). The low reactivity of **2a** in the presence of a good dienophile is surprising, but the adduct **15** forms quantitatively and was isolated in high yield (90%). Compound **13** is not a precursor to **14**, as addition of *N*-ethylmaleimide *after* generation of **2f** resulted only in isolation of **13**. Importantly, the efficient one-pot reaction to form **14** from **12** suggests that this method should also be of value for more traditional, reactive *o*-QDM chemistry.

The extension of this approach to larger polyaromatic systems *via* multifold coupling reactions began with precursor bis(diynes) **16**–**18** (Scheme 5). These compounds were easily accessible *via* Suzuki coupling (see SI). Methyl substituents were chosen to simplify structural analysis and promote crystallinity of the target bis(*o*-QDMs). Upon treatment of **16**–**18** with 2.2 equiv of $Cp_2Zr(pyr)(Me_3SiC{\equiv}CSiMe_3)$ followed by excess benzoic acid, bis(*o*-QDMs) **2g–i** were isolated in high yields. The intermediate ZrPAHs **1g–i** were isolated as crude solids, re-suspended in benzene or toluene, and then treated with benzoic acid, but isolation of the ZrPAH is optional. While $Cp_2Zr(pyr)(Me_3SiC{\equiv}CSiMe_3)$ is an extremely convenient reagent (especially on a small scale), the Negishi protocol (*vide supra*) is often preferred. Thus, to demonstrate both the scalability and applicability of this protocol, it was employed to isolate 1.5 g of **2g** (89% yield). The structures of **2g–i** were elucidated by X-ray crystallography (Figure 2b–d). Each diene unit was determined to possess a similar amount of distortion as **2a**, as determined by their diene torsion and biphenyl twist angles. They also have qualitatively similar stabilities. To the best of our knowledge, these are the first examples of isolable compounds with more than one *o*-QDM subunit.

The isolable *o*-QDMs are structurally fascinating, but their promise for post-coupling functionalization is perhaps of greater interest. Diels-Alder reactions are the obvious choice; however, initial difficulties with the aromatization of **15** prompted the establishment of an alternative route to valuable functionality. A 1,4-addition of H_2 across the diene is

potentially the simplest transformation and would give unique PAHs decorated with alkyl groups. Such functionality, which is currently difficult to install, improves solubility and often promotes liquid crystallinity, with minimal perturbation of electronic properties. A selective 1,4-addition was observed upon exposure of **2a–b** and **2g–i** to 1 atm of H_2 over Pd/C to furnish alkylated PAHs **19–23** in good to very high yields (Scheme 6). A wide range of alkylated PAHs are now within reach using this approach.

As a test for applicability of the method to more demanding multifold couplings, PAHs containing three and five *o*-QDM units were targeted (**2j** and **2k**; Scheme 7). Remarkably, treatment of tris(diyne) **24** and pentakis(diyne) **25** with $Cp_2Zr(pyr)(Me_3SiC{\equiv}CSiMe_3$ (3.3 and 5.5 equiv), followed by excess benzoic acid, furnished **2j** and **2k** in excellent isolated yields (89 and 83%). Structural proof is provided by the characteristic ^1H NMR spectra of these isolable *o*-QDMs (*vide supra*). Synthesis of helical PAH **2k** not only demonstrates the high efficiency of the method, this compound is also the first member of a new class of helicenes with alternating angular and linear fusion. Hydrogenation of **2j** furnished the angular PAH **26** (Scheme 6) in 66% yield.

The method presented above is a highly efficient means to fuse multiple rings into a PAH that contains the valuable zirconacyclopentadiene functionality (ZrPAH). Protiodemetallation of these ZrPAHs gives a new entry to PAHs containing embedded *o*-QDMs. The high yield of these reactions suggests their suitability for the synthesis of even larger PAHs and graphene nanostructures. The discovery of a general class of isolable *o*-QDMs, which are usually generated as fleeting intermediates, opens new possibilities, including reaction with other reactive intermediates (e.g., arynes) or precise control of stoichiometry (e.g., for a Diels-Alder polymerization). Finally, and perhaps most importantly, these ZrPAHs are poised for use in any of the known zirconocene transfer reactions and should provide direct access to large heteroatom-functionalized PAHs and carbon-rich nanostructures.[34]

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Initial phases of the synthetic work were funded by the National Science Foundation under Grant No. CHE-0314709. Other aspects of the work were supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Chemical Sciences, Geosciences, and Biosciences Division under Contract No. DE-AC02-05CH11231, and by the University of California, Berkeley. We also acknowledge the National Institutes of Health for funding of the ChexRay X-ray crystallographic facility (College of Chemistry, University of California, Berkeley) under grant no. S10-RR027172. We thank Daniel S. Levine for crystallographic analysis of compound 1a and Andy I. Nguyen for helpful discussions.

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24. Example based on:a) Bouit PA, Escande A, Szűcs R, Szieberth D, Lescop C, Nyulászi L, Hissler M, Réau R. J Am Chem Soc. 2012; 134:6524–6527. zirconacylopentadiene intermediate: [PubMed: 22475075] (b) Guo X, Wang S, Enkelmann V, Baumgarten M, Müllen K. Org Lett. 2011; 13:6062–6065. rhodacylopentadiene intermediate: [PubMed: 22032236]
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30. The annulated aromatic rings are one reason that **2a** exhibits higher stability than non-annulated o-QDMs. This can be explained by invoking Clar's rules, which predict that the diradical resonance structure (Figure 1) is much less important in describing the electronic structure of **2a** compared to an analogous non-benzannulated *o*-QDM.
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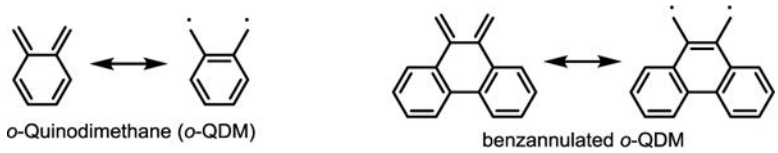


Figure 1.

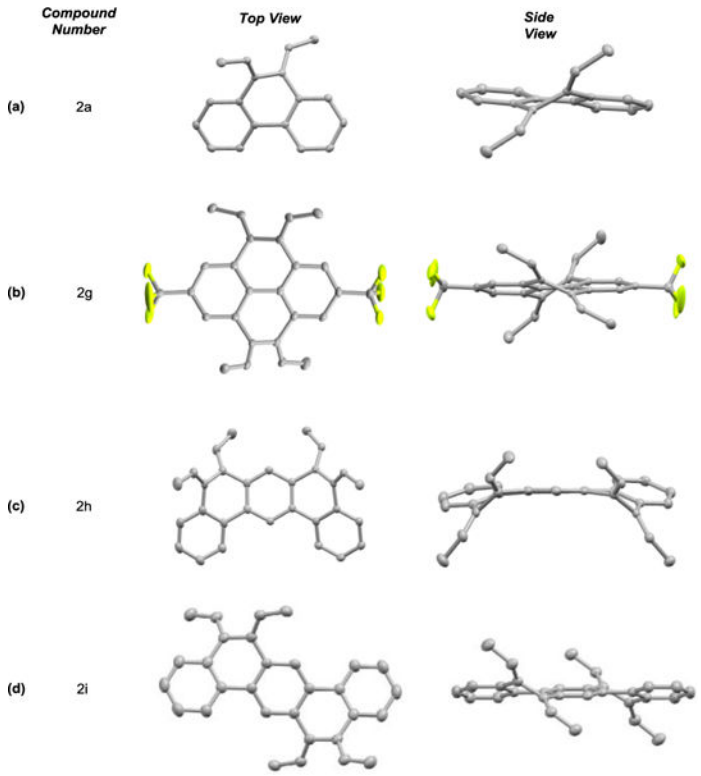
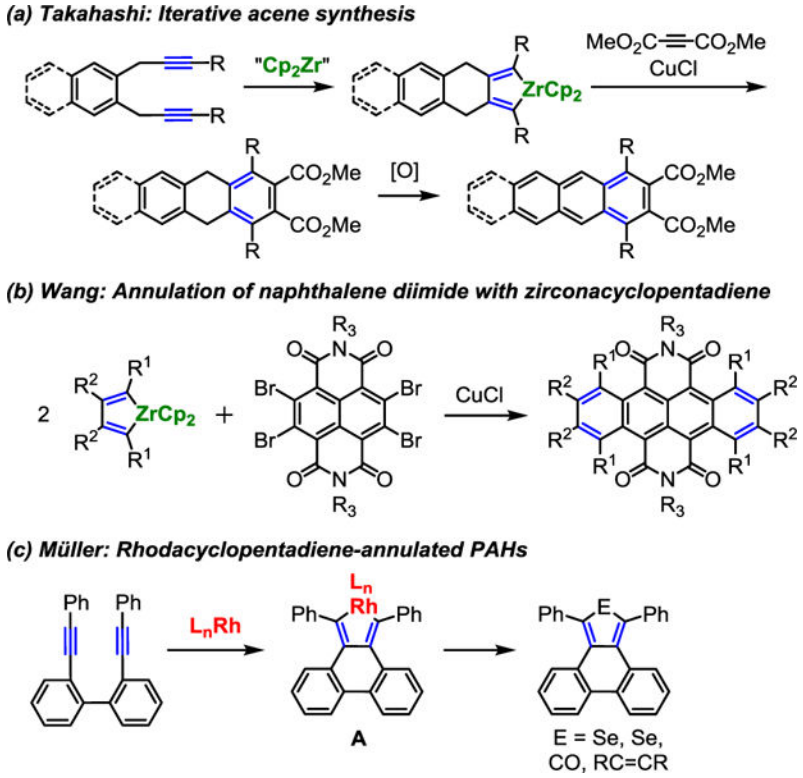
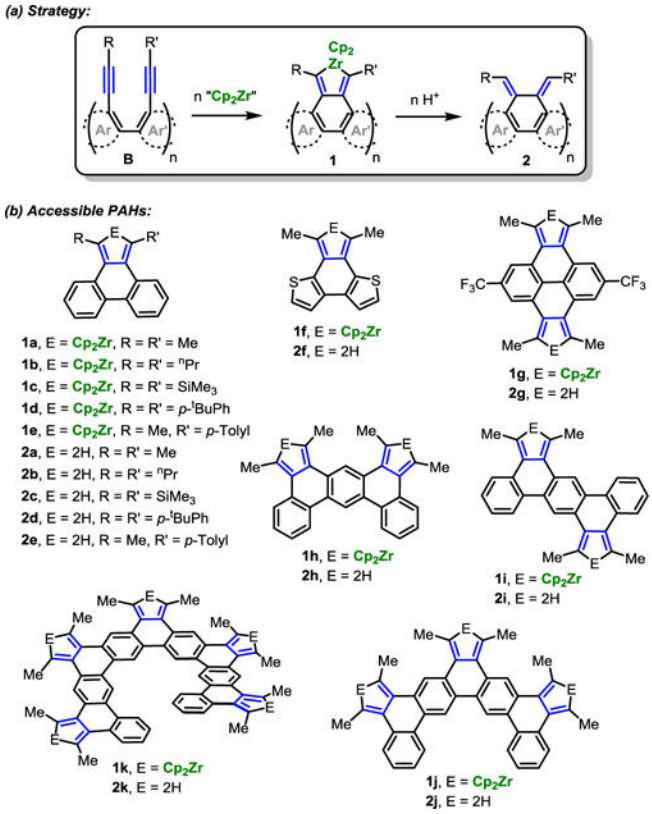


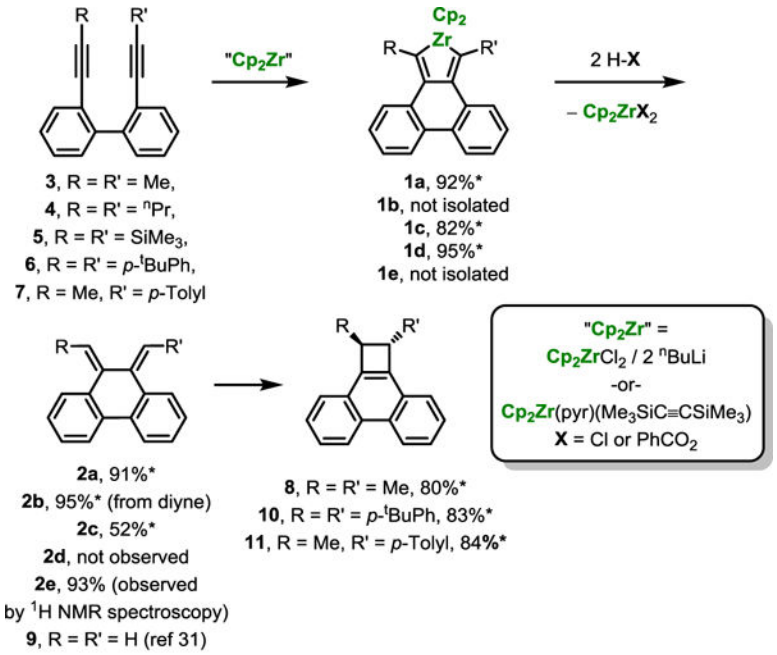
Figure 2.



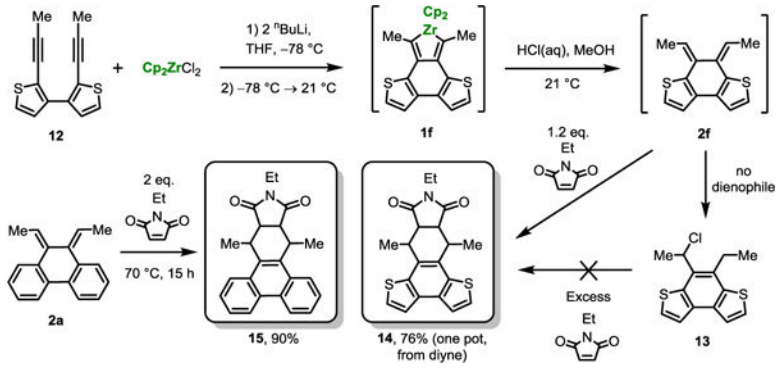
Scheme 1.



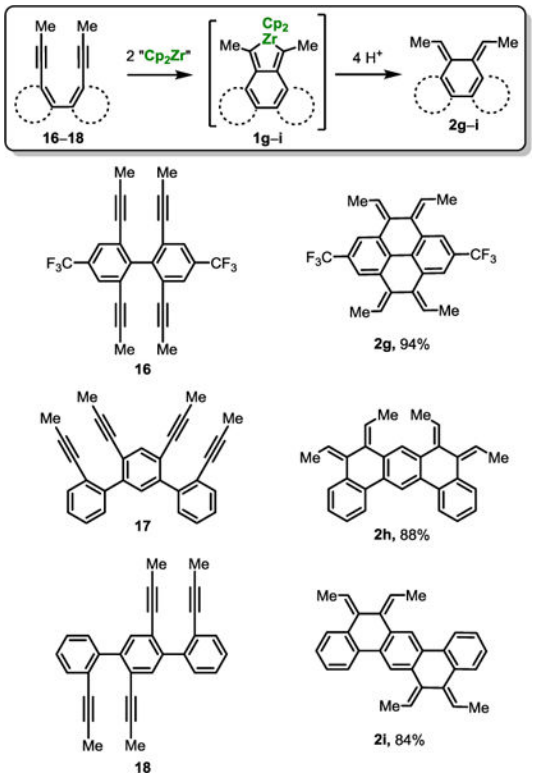
Scheme 2.



Scheme 3.



Scheme 4.



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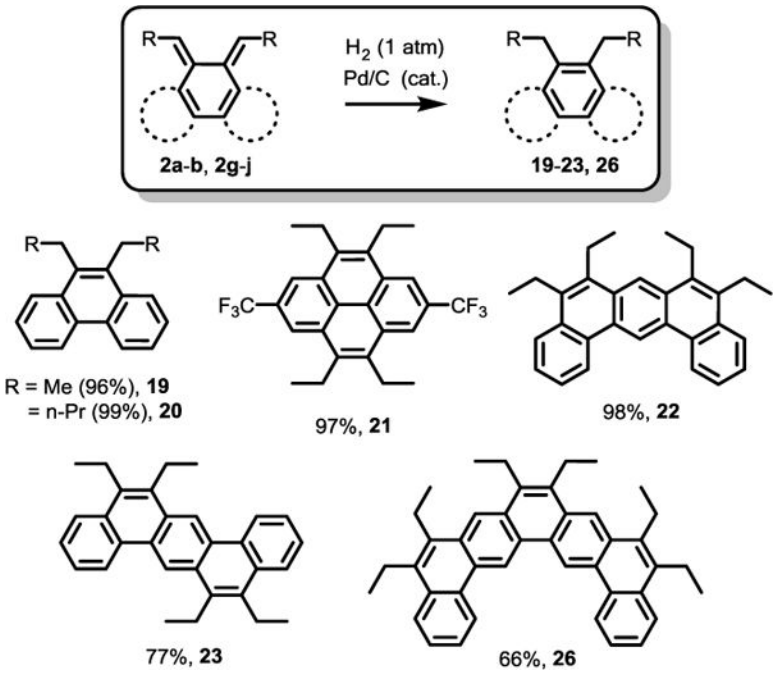
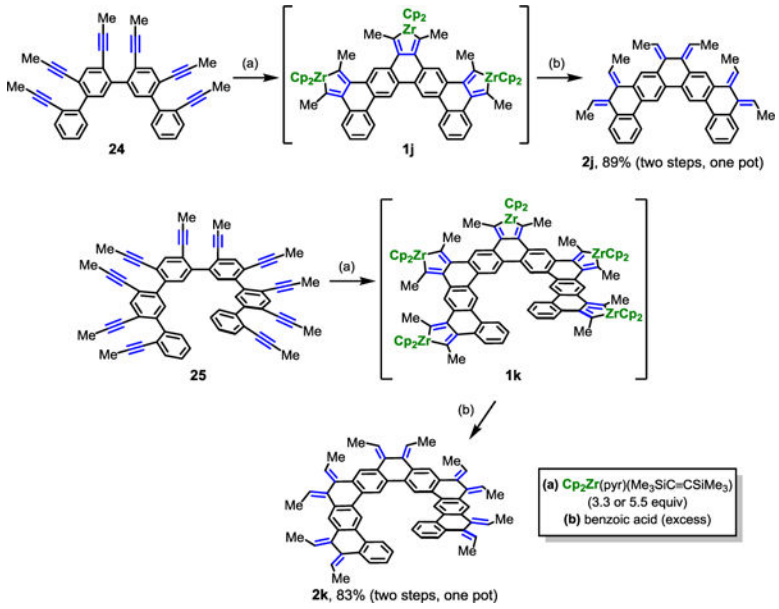


Scheme 6.



Scheme 7.