Polycyclic Aromatic Triptycenes: Oxygen Substitution Cyclization Strategies

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1021/ja3018253">http://dx.doi.org/10.1021/ja3018253</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Chemical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Author's final manuscript</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sat May 12 08:08:41 EDT 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/78290">http://hdl.handle.net/1721.1/78290</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
# Polycyclic Aromatic Triptycenes: Oxygen Substitution Cyclization Strategies

<table>
<thead>
<tr>
<th>Journal:</th>
<th><em>Journal of the American Chemical Society</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>Draft</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Communication</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>n/a</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>VanVeller, Brett; University of Wisconsin–Madison, Biochemistry Schipper, Derek; University of Ottawa, Chemistry; Massachusetts Institute of Technology, Swager, Timothy; Mass. Inst. of Tech., Chemistry; Massachusetts Institute of Technology, Department of Chemistry 18-597</td>
</tr>
</tbody>
</table>
Polycyclic Aromatic Triptycenes: Oxygen Substitution Cyclization Strategies

Brett VanVeller, Derek J. Schipper, Timothy M. Swager*

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States
Supporting Information Placeholder

ABSTRACT: The cyclization and planarization of polycyclic aromatic hydrocarbons with concomitant oxygen substitution was achieved through acid catalyzed transesterification and oxygen-radical reactions. The triptycene scaffold enforces proximity of the alcohol and arene reacting partners and confers significant rigidity to the resulting π system, expanding the tool set of iptycenes for materials applications.

Polycyclic aromatic hydrocarbons (PAH) have attracted considerable attention because of the promise these materials hold for molecular electronics. Inherent to the structure of many PAHs is an overall planar topology, which is generally desired to create the highest π-orbital overlap and electron delocalization. The majority of PAHs are accessed by intramolecular oxidative cyclodehydration of adjacent phenylene vertices through the Scholl reaction (1→2). This chemistry has seen broad application because of its ability to form multiple bonds between functionalized C-H bonds under mild conditions with relatively high efficiency. Indeed, two dimensional graphene nanoribbons up to 12 nm in length have been synthesized from preassembled frameworks. However, tolerance of heteroatoms—which can dramatically modify the electronic properties of PAHs—has proven a synthetic challenge.

The rigid three-dimensional structure of iptycene-derived scaffolds has proven to be an exceptionally versatile motif for creating high performance and new material properties. Recently, our group reported an efficient synthesis of 1,4-dibromotriptycene diols (TD, 3) through a rhodium-catalyzed [2+2+2] cycloaddition. To expand the diversity of iptycene scaffolds for PAH applications, we envisioned 3 might be elaborated through palladium cross-coupling methods (3→4). The resulting extended π-system (4) bears close proximity to the TD hydroxyl group—enforced by the triptycene scaffold—affording the opportunity for cyclization reactions to create oxygen substituted PAHs (5). We recently demonstrated this principle for cyclization of alkyne π-systems to transition between two classes of conjugated polymer backbones. Herein, we report the extension of this principle for the cyclization and planarization of a variety of arene π-systems—through both oxidative and non- oxidative methods—to give triptycene incorporated PAHs with oxygen heteroatom substituents (4→5). Further, the [2,2,2]-ring system on which the triptycene is based appears to confer considerable rigidity, resulting in extremely sharp photophysical features, introducing a new aspect of iptycene structure for electronic material design.

Compound 3 provided a convenient branch point to explore the proposed cyclization through diversification using palladium catalyzed Suzuki-Miyaura cross-coupling; to this end, 6 was synthesized in excellent yield (Scheme 1). The Scholl reaction is generally thought to proceed through an aromatic cation, and we envisioned the proximal electron rich oxygen of the hydroxyl group might be coaxed into reaction with the oxidized arene. Unfortunately, under several Scholl-type oxidants (FeCl₃, DDQ, CuCl₂) only starting material was isolated. Concurrently, we also tested conditions likely to generate an oxygen-centered radical (Ce⁴⁺, Pb(OAc)₄, Cu⁴⁺/S₅O₆²⁻). Encouragingly, cerium ammonium nitrate produced small amounts of the half-cycloized intermediate, but the Cu⁴⁺/S₅O₆²⁻ protocol gave the fully cycloized 7 in good yield with spot-to-spot conversion by TLC. The structure of 7 was unambiguously confirmed by X-ray crystallography (Figure 1). Reports of the Cu⁴⁺/S₅O₆²⁻ conditions have invoked both aromatic radical cations and oxygen-centered radical mechanisms, but we believe the oxygen-radical hypothesis to be the dominant pathway for this system (vide infra).

We next applied these conditions to higher order π-systems (11). Compound 8—an intermediate in the synthesis of TDs—was further elaborated to 9 by a [2+2+2] cycloaddition with diphenylacetylene and Wilkinson’s catalyst. Application of the Cu⁴⁺/S₅O₆²⁻ conditions lead to successful cyclization of the TD hydroxyl groups
(10) as anticipated, but failed to convert 9 to a fully cyclized compound. This observation lends support to our oxygen-radical hypothesis for cyclization, as an arene centered cation might have lead to a fully cyclized product by a Scholl-type mechanism. Attempts to cyclize the remaining arenes with FeCl₃ lead to complex oligomeric mixtures (11) most likely coupled para to the installed oxygen following established Scholl reactivity for such compounds. The proposed structure 11 is based on UV/vis (see Figure 3b and associated text for explanation) and MALDI-TOF mass spectrometry.

Scheme 1. Oxidative cyclization of phenylene substrates.

The successful cyclization of both transetherification substrates (14 and 16) was marked by the removal of rotational disorder in their ¹H NMR spectra (Figure 2). For both 13 and 15, steric clash between the methyl ether and TD hydroxyl groups lead to broadening of these signals as well as the aryl-H signals on the "wings" of the TD, possibly due to rotomers and intramolecular hydrogen bonding. Upon cyclization and planarization, the rotational isomerism—in addition to the signals for the hydroxyl proton and methyl ether—was removed.

The effects of the cyclization reaction on all of the π-systems under study were most distinctly visualized in their UV/vis and fluorescence signatures relative to their respective starting materials (Figure 3a-d). The absorbance maxima for each compound red-shift by almost 100 nm after cyclization (reducing the Stokes shift, Table 1). This closing of the band gap is ascribed to both the increased planarity and the presence of electron-rich oxygen donor atoms that raise the HOMO level. Additionally, distinctly sharper absorbance and emission features (vibrational fine structure) for each compound were also observed. Finally, as expected, there is an associated increase in fluorescence quantum yield for the cyclized rich aromatics. Further, we also desired a milder alternative as these oxidative conditions have been shown to oxidize the benzyltic position of appended alkanes—substituents relevant for PAH solubility.

We were inspired by the acid catalyzed transetherification of 3-methoxythiophenes¹⁰ and synthesized 13 in a similar manner as for 12. In the context of 13, the rigid TD scaffold holds the alcohol in close proximity to the 3-position of the thiophene (Scheme 2). Thus, protonation of the thiophene ring with p-toluenesulfonylic acid in refluxing toluene allowed for 6-membered transition state attack—via a C=OMe oxonium resonance structure—and substitution of the TD alcohol at the thiophene 3-position to give the cyclized product 13 in high yield (spot to spot conversion by TLC). The cyclization was confirmed by X-ray crystallography (Figure 1).

The acid catalyzed transetherification of 3-methoxythiophenes has largely been applied for the attachment of alkyl side chains. Its application for annulation and planarization of π-systems is rare.¹⁶ We envisioned this reaction might hold promise more generally as a strategy for electron rich, oxygen-substituted, phenyl systems. Such systems have been problematic for PAHs because they are prone to quinone formation under the Scholl conditions. Further, the largely hydrocarbon family of PAHs are generally tolerant of prootic acid conditions. To this end, we synthesized 15 from 3 and, in the presence of acid in boiling mesitylene, 16 was synthesized in excellent yield.¹⁷ Finally, the structure was confirmed by X-ray crystallography (Figure 1).
products relative to their precursors (Table 1). These observations result from the removal of vibrational relaxation through planarization. Further, the [2,2,2] ring system of the triptycene scaffold enforces significant rigidity, leading to particularly sharp spectral features. An exception to this being 16, which shows slightly broadened vibrational transitions likely due to rotational relaxation from the methoxy substituents. As mentioned above, the proposed structure of 11 is partially based on its absorbance spectrum (Figure 3b), which is indicative of a tribenzo[fgijrst]pentaphene chromophore and supports the notion that portions of the oligomer are at least partially cyclized as 11 did show signs of electrochemical cyclization (see Supporting Information for further details).

Figure 2. ¹H NMR comparison of (a) 13→14 and (b) 15→16. Signal assignments based on 1D coupling constants and 2D NMR experiments (see Supporting Information for further details).

Cyclic voltammetry was used to investigate the redox behavior of the cyclized compounds (Figure 3e-h). Planarization and introduction of electron-donating oxygen atoms to the π systems was anticipated to encourage oxidation by raising the HOMO level. This was indeed the case, as both 7 and 10 showed reversible oxidation peaks upon cyclization where 6 and 9 showed no redox behavior over the voltage scanned. Additionally, the more electron rich arenes in 14 and 16 showed two resolved single-electron oxidation peaks at lower potentials relative to 13 and 15 upon cyclization (Table 1).

Figure 3. (a-d) UV/Vis absorbance (solid) and fluorescence (dashed) spectra in CHCl₃; (e-h) Cyclic voltammograms in CH₂Cl₂ with nBu₄NPF₆ as electrolyte (see Supporting Information for further details).

To summarize, we have developed a strategy that takes advantage of the surrounding molecular architecture for the enforced proximity of reacting partners. The cyclization reactions succeed in the formation of low strain six-membered rings for extended planar PAHs with installed oxygen substituents and incorporated triptycene scaffolds. The triptycenes—in addition to fixing the hydroxyl group and arene into a favorable position—contribute significant rigidity to the π-systems. This effect on π-systems appears to be a design aspect not yet reported for three-dimensional iptycene materials. While this strategy was demonstrated to work under oxidative conditions commonly employed for PAH syntheses, the pre-organized framework also encouraged transesterification reactions with suitably functionalized arenes under Bronsted acid con-
ditions. This acid-catalyzed mode of reactivity has not seen broad use in the field of PAH synthesis, and might provide an avenue towards more heteroatom-substituted platforms. We hope to extend this strategy to other aromatic moieties and side chain functional groups.

Table 1. Summary of photophysical data.

<table>
<thead>
<tr>
<th></th>
<th>abs</th>
<th>em</th>
<th>log ε</th>
<th>Φp</th>
<th>τp</th>
<th>E_on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>λ_max a</td>
<td>λ_max a</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[nm]</td>
<td>[nm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>242</td>
<td>363</td>
<td>4.44</td>
<td>0.20</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>358</td>
<td>359</td>
<td>4.56</td>
<td>0.81</td>
<td>1.43</td>
<td>1.28</td>
</tr>
<tr>
<td>9</td>
<td>242</td>
<td></td>
<td>4.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>360</td>
<td>387</td>
<td>4.58</td>
<td>0.83</td>
<td>1.5</td>
<td>1.11</td>
</tr>
<tr>
<td>11</td>
<td>455b</td>
<td>465</td>
<td>0.70</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>275</td>
<td>407</td>
<td>3.20</td>
<td>0.9</td>
<td>1.87</td>
<td>0.53</td>
</tr>
<tr>
<td>14</td>
<td>384</td>
<td>386</td>
<td>4.58</td>
<td>0.30</td>
<td>0.97</td>
<td>0.83/1.33</td>
</tr>
<tr>
<td>15</td>
<td>302</td>
<td>375</td>
<td>4.00</td>
<td>0.03</td>
<td>1.39</td>
<td>1.08</td>
</tr>
<tr>
<td>16</td>
<td>380</td>
<td>388</td>
<td>4.44</td>
<td>0.71</td>
<td>2.22</td>
<td>0.95/1.24</td>
</tr>
</tbody>
</table>

*All values measured in CHCl₃. *Based on red-most abs λ_max. †All values measured in CH₃Cl with nBuNPF₆ as electrolyte.

ASSOCIATED CONTENT

Supporting Information. Experimental protocols and analytical data. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author
* tswager@mit.edu

ACKNOWLEDGMENT

B.V. was supported by the Natural Science and Engineering Council of Canada (NSERC) and in part by an NIH BRP grant (R01 AG026240-01A1). D.J.S. was supported by an NSERC Postdoctoral Fellowship. This work was supported in part by the Air Force Office of Scientific Research (FA9550-10-1-0395). We wish to thank Dr. Yu Lin Zhong for assistance with electrochemical measurements and Dr. Michael Takase for X-ray crystal structures.

REFERENCES

(b) Kovacic, P.; Jones M. B. Chem. Rev. 1987, 87, 357.
(39) Liberated methanol reacted with the acid catalyst to form p-toluenesulfonic acid methyl ester under the reaction conditions. This biproduct coeluted with the product during chromatography, diminishing the isolated yield.
Rigid scaffold enforces close proximity of alcohol and reacting partner

Cyclization

Oxygen radical
n = 1, X = C-H

Acid catalyzed
n = 0, X = S
n = 1, X = C-H