Bay-Region-Selective Annulative π-Extension (APEX) of Perylene Diimides with Arynes

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Abstract

A bay-region-selective annulative π-extension (APEX) reaction of perylene diimides (PDIs) has been achieved by means of in-situ generated reactive arylene intermediates. This method provides an efficient one-pot π-extension at the short axis of PDIs in a sequential manner. Mechanistically, an inverse-electron-demand Diels–Alder reaction might be operative for the transformation.

Key words

annulative π-extension, perylene diimides, arynes, Diels–Alder reaction, coronene diimides, polycyclic aromatic hydrocarbons

Perylene diimides (PDIs) are useful chemical scaffolds because of their rigid perylene π-conjugated systems and their electron-withdrawing imide groups. These unique π-systems bestow attractive optoelectronic properties that have contributed to versatile applications, for example, as fluorescent materials, as laser compositions, and even in supramolecular chemistry. Therefore, a variety of PDI derivatives, together with methods for their functionalization, have been developed in attempts to improve and/or modify the π-character of PDIs. The π-character of PDIs can be modulated by π-extensions of PDI in two ways: along the longitudinal (long-axis) or along the transverse (short-axis) molecular axis. Although longitudinal modifications of PDIs have been well studied for the development of near-infrared-absorbing materials, the corresponding transverse extensions are less developed due to difficulties in synthesis. Müller and co-workers demonstrated a π-extension of PDIs in the bay-regions (the transverse concave armchair edges) through several steps, including bromination, Suzuki–Miyaura coupling, and cyclization [Scheme 1(a)]. As demonstrated by other researchers, lateral π-extension of PDIs relies on stepwise halogenation, coupling reactions, and cyclization or oxidation reactions, which reduces the synthetic efficiency and availability of the π-extended PDIs and loses the opportunity for further π-extension and functionalization in later stages of the process. Therefore, the development of direct and step-economical methods for obtaining π-extended PDIs is in high demand.

Recently, the annulative π-extension (APEX) reaction has attracted much interest in relation to the synthesis of polycyclic aromatic compounds (PACs), because the APEX reaction permits a one-step π-extension of nonfunctionalized polycyclic aromatic hydrocarbons (PAHs) or heteroaromatics without any prior functionalization, such as halogenation, thereby providing a variety of nanographenes or heteroatom-containing PACs that are difficult to access by conventional methods. For example, we have developed K-region (concave armchair edge)-selective APEX reactions of PAHs such as phenanthrenes, pyrenes, corannulene, and chrysene, catalyzed by cationic palladium complexes. In addition, APEX reactions of PAHs in the bay-region have also been demonstrated by Clar and Zander, and by the groups of Scott, Wu, Matsuda and Stork, Kubo, Peña, and Hoye. These reactions involve Diels–Alder-type reactions with dienophiles such as alkenes, quinones, or arynes [Scheme 1(b)]. However, the range of available substrates is limited to perylene, benzoperylene, and bisanthene, exclusively, due to the harsh reaction conditions, and no examples of bay-region-selective APEX of PDIs have been reported despite the high demand for such processes.
Scheme 1 (a) The classical stepwise π-extension method and the bay-region-selective annulative π-extension (APEX) method (this work) for π-extended perylene diimides. (b) Previously developed APEX reaction of perylene with arynes (Stork/Matsuda, Scott, Kubo, Peña, Hoye).

Table 1 Screening of the reaction conditions for bay-region-selective APEX reactions of perylene diimide 1 with benzyne precursors 2

<table>
<thead>
<tr>
<th>Entry</th>
<th>Deviations from the standard conditions for the reaction of 1a with 2a</th>
<th>Yield (%) of 3aa</th>
<th>Yield (%) of 4aa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>63 (37)$^c$</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>120 °C</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>24 h</td>
<td>58</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>2a (5.0 equiv)</td>
<td>38</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>2b instead of 2a</td>
<td>24</td>
<td>n.d.$^d$</td>
</tr>
<tr>
<td>6</td>
<td>MeCN instead of PhCN</td>
<td>trace</td>
<td>n.d.</td>
</tr>
<tr>
<td>7</td>
<td>DMF instead of PhCN</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>8</td>
<td>toluene instead of PhCN</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>9</td>
<td>CsF instead of KF</td>
<td>35</td>
<td>trace</td>
</tr>
<tr>
<td>10</td>
<td>TBAT instead of KF</td>
<td>13</td>
<td>trace</td>
</tr>
<tr>
<td>11</td>
<td>1b instead of 1a</td>
<td>68 (46)$^e$</td>
<td>9$^f$</td>
</tr>
</tbody>
</table>

$^a$ Standard reaction conditions: 1a (0.10 mmol, 1.0 equiv), 2a (2.0 equiv), KF (5.0 equiv), PhCN (2.0 mL), 160 °C, 48 h.
$^b$ $^1$H NMR yield determined by using CH$_2$Br$_2$ as an internal standard.
$^c$ Isolated yield.
$^d$ n.d. = not detected.
$^e$ $^1$H NMR yield of 3ba.
$^f$ $^1$H NMR yield of 4ba.
Here, we report the first bay-region-selective APEX reactions of PDIs with arynes as π-extending agents for the synthesis of π-extended PDIs [Scheme 1(a); bottom].

Optimization of the reaction conditions was performed by using the dimesityl-substituted PDI 1a as a standard substrate (Table 1). PDI 1a was treated with the benzene 11 precursor 2-(trimethylsilyl)phenyl triflate (2a) (2.0 equiv) and KF (5.0 equiv) in benzonitrile as the solvent at 160 °C. After 48 hours, 1a was almost consumed (>90% conversion) to afford the single-APEX product 3aa and the double-APEX product 4aa in 63% and 13% NMR yields, respectively (Table 1, entry 1). However, the separation of product 3aa from 4aa was difficult, and 3aa was obtained in only 37% isolated yield. Reactions at a lower temperature or for a shorter reaction time resulted in slightly lower yields of the product (entries 2 and 3). The amount of 2a affected the ratio of 3aa and 4aa; however, an exclusive synthesis of the doubly-π-extended PDI 4aa was not achieved by changing the reaction conditions (entry 4). The use of 2-diazoniobenzoate (2b) instead of 2a gave an inferior result, probably due to the thermal lability of 2b (entry 5; 24% NMR yield of 3aa). An examination of various solvents revealed that benzonitrile is the optimal solvent [for details, see the Supporting Information (SI)]. In reactions using CsF or tetrabutylammonium difluorooctysilicate (TBAT) instead of KF, 3aa was exclusively obtained, but in a lower yields of 35% and 15%, respectively (entries 9 and 10); none of the double-APEX product 4aa was generated. The reaction of PDI 1b, which had 6-undecyl groups on the nitrogen atoms, was also examined, and comparable results to those for 1a were obtained (entry 11).

Next, we explored the substrate scope of arynes in the bay-region-selective APEX reactions of PDIs 1a and 1b (Scheme 2). When the commercially available 2,3-naphthaldehyde precursor 2c was subjected to the APEX reaction with 1a under the optimized reaction conditions shown in entry 1 of Table 1, only traces of the desired APEX product 3ac were observed in the crude mixture. This situation was not markedly improved by changing various reaction conditions, such as the temperature, the amounts of reagents, or the solvent. This might be due to the instability of the 2,3-naphthaldehyde intermediate under severe thermal reaction conditions.12 However, the reaction of the highly soluble 6-undecyl-substituted PDI 1b proceeded smoothly in MeCN at 120 °C to afford the APEX product 3bc in 49% NMR yield and 36% isolated yield. On the other hand, the 9,10-phenanthrylene precursor 2d reacted with PDIs 1a and 1b with good efficiency to give the corresponding single-APEX products 3ad and 3bd, respectively. In these reactions, although traces of the corresponding double-APEX products were also detected in the crude mixture, products 3bc, 3ad, and 3bd were easily isolated by simple chromatography techniques. When other arynes, such as electron-deficient 2,3-pyridyne13 or alkyl- or aryl-substituted alkynes were subjected to the above reaction conditions, the starting PDIs were recovered without the formation of any APEX products. These results suggest that highly reactive triple bond, such as those of aromatic-hydrocarbon-based arynes are necessary for bay-region-selective APEX reaction of PDIs (see SI for details).

To clarify the reaction profiles and to explore the potential of our bay-region APEX reaction, we performed sequential APEX reactions (Scheme 3). First, the single-APEX product 3aa was further subjected to the optimized APEX reaction conditions with 2a in an attempt to obtain the double-APEX product 4aa. However, a quite-low conversion of 3aa and the formation of a small amount of 4aa were observed [Scheme 3(a)], which is inconsistent with the result obtained in entry 1 of Table 1. This result implies that the actual intermediate for the second bay-region APEX reaction in entry 1 of Table 1 might not be 3aa, but instead 3aa–H2, the primary product of the Diels–Alder reaction before the ejection of two hydrogen atoms that completes the APEX reaction through rearomatization. On the contrary, the APEX reaction of 3ad with 2a afforded the π-extended PDI 5a along with a good recovery of 3ad [Scheme 3(b)]. The resulting nonsymmetrical nanographene diimide structure might provide a new entry to π-extended coronene diimides (CDIs) for future photophysical and electrochemical applications.14
Stimulated by these difference in reactivities between PDIs in the bay-region-selective APEX reaction, we performed DFT calculations at the B3LYP/6–31G(d) level of theory. Scott and co-workers reported that the bay-region-selective APEX reaction of unsubstituted PAHs such as phenanthrene, perylene and bisanthene with acetylene occurs through a Diels–Alder reaction with subsequent aromatization.10e Furthermore, they showed experimentally and computationally that perylene is the smallest PAH that affords the APEX product, with an activation energy of 30.0 kcal/mol for the Diels–Alder reaction step. In our calculations using PDIs 1a, 3aa, and 3ad as dienes with benzyne as a dienophile, inverse-electron-demand Diels–Alder reactions15 successfully afford the dihydro-APEX products 3aa–H2, 4aa–H2, and 5–H2 through transition states TS1–TS3, respectively (Scheme 4). The activation barrier to TS1 was calculated to be 14.9 kcal/mol, which is relatively low and supports the smooth reaction progress observed in Table 1.16 On the contrary, the activation energies from 3aa and 3ad to TS2 and TS3 were calculated to be 17.1 and 15.7 kcal/mol, respectively, probably due to the increased LUMO energy of 3aa (–3.24 eV) and 3ad (–3.16 eV) compared with

Scheme 3  APEX reactions of 3aa and 3ad for the synthesis of further π-extended PDIs 4aa and 5

Scheme 4  DFT calculation of the activation energies in Diels–Alder reaction of 1a, 3aa, and 3ad with benzyne
that of 1a (−3.42 eV). Although the reason for the lower activation energies in TS3 than TS2 is unclear, the present calculations well reflect the experimental results that Diels–Alder reactions occur not in 3aa, but also in 1a and 3ad. Further tuning of arynes (HOMO) and PDIs (LUMO) should lead to even-more-efficient Diels–Alder APEX reactions at nonfunctionalized bay-regions of PDIs.

In summary, we have demonstrated the first bay-region-selective APEX reaction of PDIs by Diels–Alder reactions with arynes.17 This method gave the transversally π-extended PDIs in a single operation from unfunctionalized PDIs. Even nonsymmetrical π-extended PDIs, which are difficult to synthesize by conventional methods, were obtained with high efficiency. DFT calculations suggested that the bay-region APEX reaction probably proceeds through an inverse-electron-demand Diels-Alder reaction with a barrier of about 14.9–15.7 kcal/mol. We believe that our APEX method will provide an alternative synthetic tool for activation energies in Diels–Alder reactions of PDIs by Diels–Alder reaction of aromatics, see: (a) Ito, H.; Ozaki, K.; Itami, K. Angew. Chem. Int. Ed. 2017, 56, 131. (b) Ito, H.; Segawa, Y.; Murakami, K.; Itami, K. J. Am. Chem. Soc. 2019, 141, 3.


(16) We also calculated each stationary point and transition state by other basis sets (See SI for details).

(17) 3a: Typical Procedure
A screw-capped glass tube containing a magnetic stirrer bar was charged sequentially with the dimesityl PDI 1a (100 μmol, 1.0 equiv, 62.4 mg), KF (0.51 mmol, 5.0 equiv, 29.5 mg), PhCN (2.0 mL), and 2-(trimethylsilyl)phenyl triflate 2a (0.20 mmol, 2.0 equiv, 60.0 mg) under a stream of N₂. The mixture was stirred at 160 °C for 48 h, cooled to r.t., and passed through a short pad of silica gel (eluents: CHCl₃). The organic solvent was removed under reduced pressure to give a crude mixture that was analyzed by ¹H NMR (CDCl₃) with CH₂Br₂ as an internal standard. The residue was purified by flash column chromatography (silica gel) to afford a mixture of 3aa and 4aa, which was further purified by gel-permeation chromatography to give 3aa as a red solid; yield: 26.4 mg (37.7 μmol, 37% isolated).

¹H NMR (400 MHz, CDCl₃): δ = 10.2 (s, 2 H), 9.32–9.27 (m, 2 H), 9.24 (d, J = 8.4 Hz, 2 H), 9.10 (d, J = 8.4 Hz, 2 H), 8.19–8.13 (m, 2 H), 7.13 (s, 4 H), 2.42 (s, 6 H), 2.25 (s, 12 H). ¹³C NMR (150 MHz, CDCl₃): δ = 163.5, 163.3, 138.8, 135.2, 134.2, 131.1, 130.0, 129.51, 129.47, 129.3, 129.2, 129.0, 128.6, 127.9, 125.1, 124.2, 123.3, 122.9, 122.5, 21.3, 17.9. HRMS (MALDI-TOF): m/z [M + H]⁺ calcd for C₄₈H₃₃N₂O₄: 701.2435; found: 701.2434.