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Controlled Regioselective Amination of Peryleneimides

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Perylenediimides (PDIs) and perylenemonoimide diesters (PMIs) can be selectively substituted at the 1,6- or 7,12- positions of the bay region, respectively, by direct amination reactions. The reactions proceed by the formation of a perylene radical anion and its subsequent oxidation, and the yields range from 20–97 %. The amination can be tuned to obtain either mono- or disubstituted perylenes by varying the oxidants involved. The presence of the imide cycle is crucial for the transformation, although the amination occurs regioselectively at the bay-region positions distant from the imide cycle.

Introduction

Since their discovery, perylenetetracarboxylic diimides (PDIs) have attracted the interest of industry and academia. Good thermal and photostability, high fluorescence quantum yields, high molar absorption, and excellent redox properties are a few characteristics that have inspired chemists to focus their attention on these versatile organic molecules.[1,2] PDIs have been utilized extensively in a variety of high-tech applications such as photovoltaics,[3] field-effect transistors,[4] biosensors,[5] organic solar cells,[3b] organic light-emitting diodes,[6] optical switches,[7] and molecular wires.[8] PDIs have also been used in several other applications, such as artificial photosynthetic systems,[9] with controlled supramolecular architectures through their high tendency for π–π stacking.[10] Similarly, perylenemonoimides (PMIs) are useful precursors for asymmetric perylene dyes. Their syntheses from commercially available perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA) as well as their halogenation and substitution have been described.[11] PMI dyes had been used in molecular photonic switches and light-harvesting studies.[12] The major hurdle in the use of perylenemonoimide dyes had been their poor solubility in organic solvents. Various approaches such as the introduction of alkylated *N*-aryl groups or aryloxy substituents at the perimeter of perylene have been used to improve solubility.[11c] The solubility of PMI dyes can be increased dramatically by the introduction of a diester moiety to the perimeter of the molecule.[13] The incorporation of a diester moiety not only resolves the solubility issue but also makes the dyes more versatile. For example, the diester moiety can later be hydrolyzed through an acidic hydrolysis to form a second anhydride group,[14] which can be used to prepare new asymmetric PDIs with two different *N*-substituted groups.[11e] The diester groups can also be hydrolyzed to dicarboxylic acids, which can in turn be used to prepare self-assembled monolayers (SAMs) for organic solar cells.

Similarly, despite the established significance and potential of PTCDA, a lack of solubility in organic solvents has kept its usage somewhat restricted. In a BASF patent (1997), Böhm et al. reported a procedure for the 1,7-dibromination, imidation, and subsequent replacement of "bay–region" bromine atoms with alkyne or phenoxy groups.[15] This method was extensively used in many labs to synthesize bay-functionalized PDIs until 2004 when Wuerthner et al. pointed out the presence of a regioisomeric impurity, namely, the 1,6-isomer, in ca. 20–25%.[16] Later, many research groups isolated and characterized 1,6- and 1,7-regioisomers of dipiperidinyl-, diphenoxy-, and dipyrrolidinyl-substituted PDIs[17a,17b] and demonstrated that the 1,6- and 1,7-isomers might have significantly different photochemical properties.[17c–17f]

Much effort has been paid to the isolation of individual isomers, mostly 1,7-substituted, but no approaches to the synthesis of isomerically pure PDIs were proposed.[18a–18j] Furthermore, as there was no method to synthesize preferentially the 1,6-isomers of peryleneimides, the knowledge of their properties and potential applications was poor. This situation changed dramatically in 2013 when the direct amination of PDIs was reported.[19a] Very recently, Rauch et al. reported the synthesis of a regioisomerically pure 1,6-isomer by a Cu-catalyzed amination.[19b] However, these two reports are somewhat controversial in terms of their reaction mechanisms and product structures.

Herein, we report the controlled highly regioselective amination of perylene mono- and diimides; isomerically pure 7-pyrrolidinyl and 1,6-dipyrrolidinyl derivatives are synthesized, and the substitution reaction can either be cat-

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alyzed by metal complexes or run catalyst-free. Depending on the substrates and the desired product (mono- or disubstituted), the reaction can be performed either at room temperature with $KMnO_4$ or atmospheric oxygen as an in situ oxidant or as a one-pot, two-step process with subsequent oxidation by pyridinium dichromate (PDC). In either case, the method is highly attractive as it does not require any halogen (or other) leaving group for the substitution to occur, and the reaction conditions are mild. Unlike the previously reported work, in our case, the substitution occurs at the bay region instead of the 2,5-positions of perylene[19a] and can also proceed without catalyst.[19b]

Results and Discussion

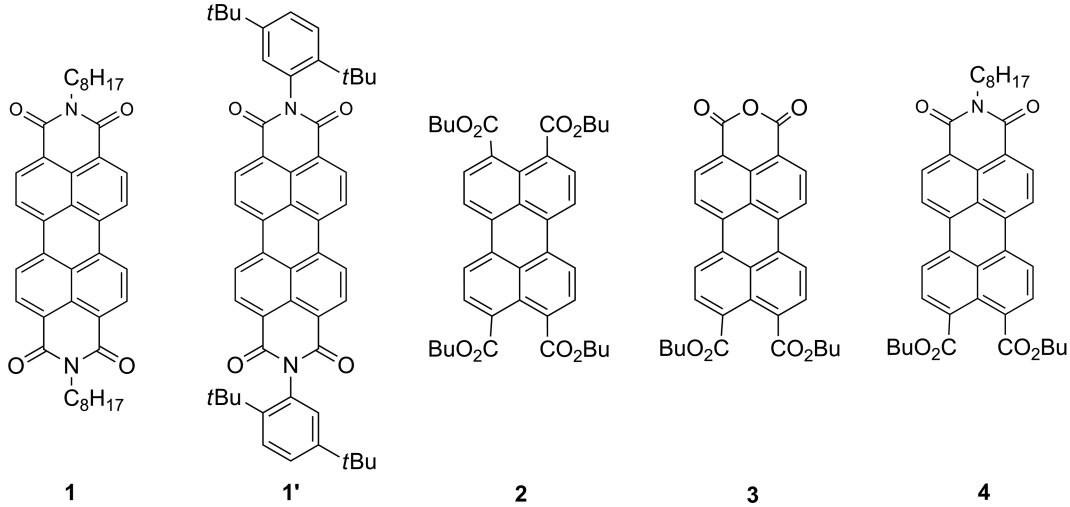
Synthesis of Precursors

The precursors **1**, **1′**, and **4** were synthesized from commercially available PTCDA by slight modification of procedures reported previously.[18g,20] The treatment of PTCDA with imidazole and the desired amine at elevated temperature yielded the *N*-alkylated PDIs **1** and **1′** in good yields. The perylene tetraester (PTE) **2** was obtained by esterification of PTCDA with an alkanol and alkyl halide in a homogeneous solution.[18g] The PTE was then selectively hydrolyzed by *p*-toluenesulfonic acid (*p*TsOH) to yield the monoanhydride–diester **3** as a precipitate, which upon imidization with *n*-octylamine and imidazole produced the PMI diester **4** as a dark red solid in 68% yield.[18g,20] The crucial step in the synthesis of **4** was the selective hydrolysis with *p*TsOH, as even a slight excess of *p*TsOH, the wrong reaction temperature, or an inappropriate solvent resulted in the formation of PTCDA. A mixture of toluene and hexane (5:1 v/v), 1.2 equiv. of *p*TsOH, and a reaction temperature of 100 °C were the optimal conditions, which prevented the second hydrolysis.

Amination of PDIs

While studying different substitution reactions, we noticed that a solution of dioctyl PDI **1** in neat pyrrolidine under argon slowly turned from red to blue upon heating. After the vial was opened and the solution was exposed to air, the color changed rapidly from blue to reddish, and green monopyrrolidine PDI **5a** was recovered from the reaction mixture along with the starting material **1**. Our attempts to isolate "the blue intermediate" for NMR spectroscopy analysis were unsuccessful, as the compound proved to be very air sensitive. However, in situ detection by UV/Vis spectroscopy was possible. A small amount of PDI in thoroughly argon-purged pyrrolidine was heated at 60 °C in a sealed cuvette, and the gradual changes in the absorption spectra were recorded. As can be seen in Figure 1, the two peaks of PDI **1** at λ = 450 and 550 nm decreased with time and were completely gone after 5 h. Instead, the newly formed compound had distinct absorption maxima at λ = 720 and 800 nm. A very similar absorption profile was reported for the chemically and electrochemically generated perylenediimide radical anion by different groups.[21a–21d] After exposure of the solution to air, the bands at λ = 720 an 800 nm disappeared, the bands at λ = 450 and 550 nm were partly restored, and a broad absorbance of monopyrrolidyl PDI **5a** appeared in the spectrum. This observation allowed us to suggest that the reaction proceeds by a radical anion pathway with separate stages for the formation of the intermediate and its oxidation to the final product.

To the best of our knowledge, the direct amination of an unsubstituted aromatic core is not very common in organic chemistry. Similar reactions on smaller aromatic rings are described as "oxidative amination" and have received limited attention.[22a,22b] In the work of Verbeeck et al.,[22a] the amination is thought to proceed by a two-step mechanism: σ^H-adduct formation followed by an oxidative rearomatization. For the direct aminations of perylenes at



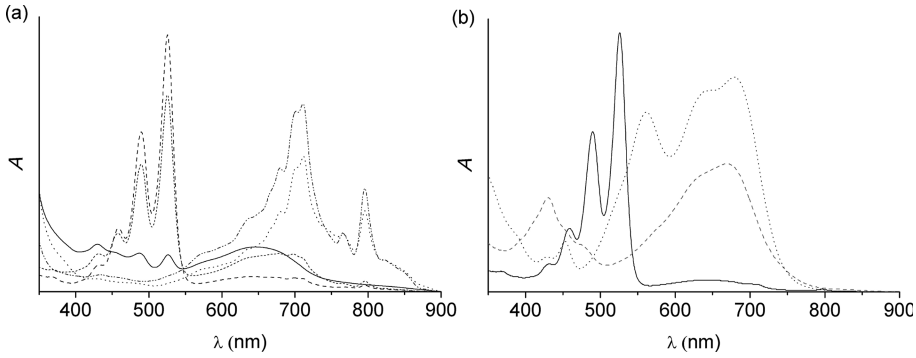
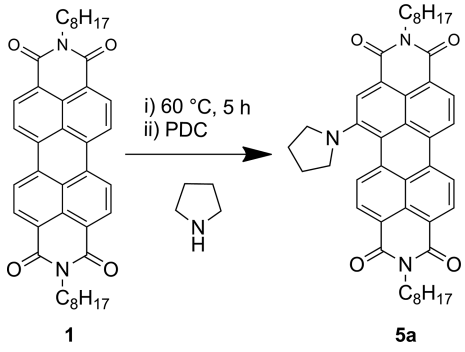


Figure 1. (a) Absorption profile for radical anion formation and oxidation of dioctyl PDI **1** in pyrrolidine. (black dashes: 0 h, short dark gray dashes: 1 h, dark gray dash dot dot: 5 h, black dots: 48 h, black solid line: vial opened). (b) Absorption of unsubstituted **1** (black solid line), monopyrrolidyl **5a** (gray dashes), and dipyrrolidyl **5b** (dark gray dots) dioctyl PDIs.

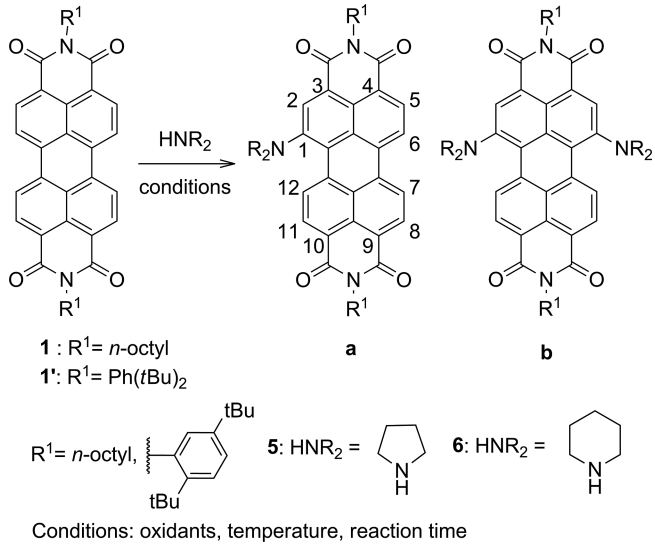
the bay region reported by Langhals and Rauch, two different reaction mechanisms have been proposed, namely, a Chichibabin-like[19a] reaction resulting in a perisubstitution of PDI or a Cu-catalyzed radical cycle, which produces bay-substituted derivatives.[19b]

First, we decided to test the catalyst-free reaction (Scheme 1) by preparation of an intermediate under an inert atmosphere and subsequent oxidation. PDI **1** was heated in pyrrolidine under an inert atmosphere for 5 h at 60 °C, and a subsequent oxidation with pyridinium dichromate (PDC) gave 20–70% yield of **5a**. The formation of product **5a** proves that the reaction proceeds through the radical anion. However, the disubstituted compound **5b** appeared only in a trace amount in this case.



Scheme 1. Amination of dioctyl PDI **1** without catalyst.

The radical anion generated was highly sensitive to air, and as a result the yield of the reaction varied greatly. Hence, the amination of the aromatic ring of PDI **1** through in situ oxidation with various oxidizing agents was explored. To our delight, pyrrolidination of dioctyl PDI **1** with $KMnO_4/AgNO_3$ as the oxidant, as reported Verbeeck et al.,[22] proceeded regioselectively to afford exclusively the 1,6-dipyrrolidinyl isomer **5b** in 65% yield (Scheme 2). The yield and the substitution sites are in good agreement with the results published by Rauch et al.[19b] However, in our case, the substitution occurred without Cu^{II} catalysis and heating.



Scheme 2. Regioselective amination of PDIs.

The effect of the oxidizing agent was studied next. When PDC was used as the in situ oxidant, the yield of monopyrrolidyl PDI **5a** was 41%, and a mixture of 1,6- and 1,7-dipyrrolidyl PDIs was also isolated in 25% total yield. When a combination of PDC/$AgNO_3$ was used for in situ oxidation, the formation of dipyrrolidyl PDI **5b** was greatly enhanced, and the yields reached 60% for the 1,6-isomer and 22% for the 1,7-isomer. The monopyrrolidyl PDI **5a** was obtained only in 15% yield in this case. However, the reaction times were as long as 6 and 4 d, respectively. Surprisingly, the use of $CuCl_2$ in the amination of PDI **1** with pyrrolidine yielded only a trace amount of dipyrrolidyl PDI **5b** after overnight stirring at room temperature. It should also be noted that we have compared the NMR spectra of the synthesized compounds with the spectra of those prepared by the traditional bromination–pyrrolidination method[17a,17b] and we have not observed perisubstituted compounds, as described by Langhals.[19a]

According to our observations, the reactivity of PDIs with different amido substituents in amination reactions,

which was also reported by Rauhe et al.,[19b] is mostly guided by the solubility. Thus, a mixture of PDI **1** with piperidine produced only a trace amount of the product even after prolonged stirring at room or elevated temperatures owing to the poor solubility of **1** in piperidine. In contrast, the reaction of much more soluble PDI **1′** with pyrrolidine or piperidine and $KMnO_4/AgNO_3$ proceeded smoothly toward the disubstituted products **5b′** and **6b′**. A complete set of reactions with $KMnO_4/AgNO_3$ and different substrates and nucleophiles is shown in Table 1. The products were isolated by preparative TLC, and the yields are given relative to the starting materials **1** and **1′**. It should be noted that the removal of the residual PTCDA from **1** and **1′** is not an easy task owing to its poor solubility, and the apparent yields might be affected by that.

Table 1. Reactions of PDIs.

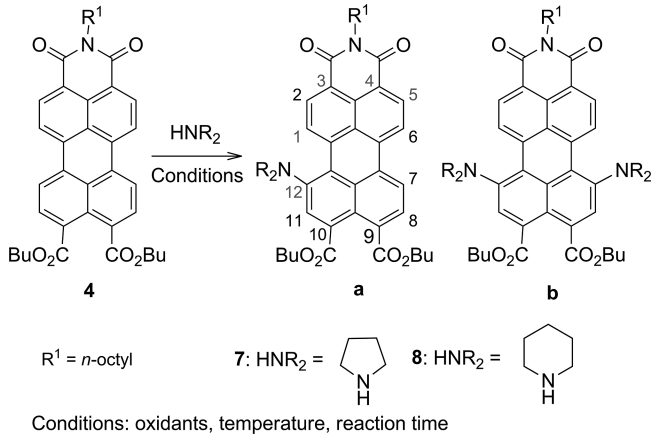
I					**1** R^1 = *n*-Octyl	
	Amine	Oxidant	*T* [°C]	Time	**a**	**b**
1		PDC (oxidation after radical anion generation)	60 °C	5 h	**5a** (20–70%)	–
2		PDC	r.t.	6 d	**5a** (41%)	**5b** (25%)[a]
3		$PDC/AgNO_3$	r.t.	4 d	**5a** (15%)	**5b** (60%)
4		$KMnO_4/AgNO_3$	r.t.	24 h	–	**5b** (65%)
5		$KMnO_4/AgNO_3$	85 °C	24 h	trace amount[b]	trace amount[b]
II					**1′** R^1 = 	
1		$KMnO_4/AgNO_3$	r.t.	24 h	–	**5b′** (69%)
2		$KMnO_4/AgNO_3$	r.t.	24 h	–	**6b′** (60%)

[a] Mixture of 1,6- and 1,7-dipyrrolidyl PDI. [b] Observed by TLC and confirmed by MS. Mostly starting material remained in the reaction.

Amination of PMIs

We decided to screen the applicability of the reaction to other perylene derivatives. To our surprise, the presence of the imide cycle played a crucial role in the amination of perylenes. The reactions of perylenetetracarboxylic ester **2** and perylene monoanhydride diester **3**[18g] under similar reaction condition failed to produce the desired products, and mostly unreacted starting compounds were recovered.

The most interesting results were obtained for the perylenemonoimide diester (PMI diester) **4**, as shown in Scheme 3. When **4** was subjected to pyrrolidination, the reaction produced a mixture of mono- and dipyrrolidinated products in 60 and 20% yield, respectively. However, most surprisingly, the substitution occurred exclusively at the bay 7- and 12-positions of the aromatic ring, which are distant from the imide cycle. This conclusion was unambiguously derived from the NMR spectroscopic data. The gradient HMBC (gHMBC) spectra of **7a** and **7b** (see Supporting Information, S24 and S28) show that the singlets of protons 8-H and 11-H at δ = 7.82 ppm (disubstituted compound **7b**) and 8-H at 8.0 ppm (compound **7a**) correlate to the C-9′ and C-10′ carbonyl carbon atoms at δ = 169 and 168 ppm, respectively. The latter two were identified by their cross-peaks with the α-butoxy protons at δ = 4.33 ppm. Simultaneously, the doublet of 2-H and 5-H correlates to the carbonyl atoms of the imide cycle, which were in turn identified by their cross-peaks with the α-amido methylene group of the octyl tail.



Scheme 3. Regioselective amination of PMI diester.

The described reaction is truly unique as it offers regiodirected substitution of perylene derivatives. The amination of PMI diester **4** with piperidine as a nucleophile works similarly and results in the formation of the mono- and disubstituted PMI diester derivatives **8a** and **8b** in 64 and 31% yield, respectively. The regiospecificity of the substitution was also preserved in this case, as confirmed by NMR spectroscopy analysis. The reaction of PMI diester **4** was screened under different conditions and with different oxidants, and the results are summarized in Table 2. Unlike the

Table 2. PMI reactions and yield.

I					**1** R^1 = *n*-Octyl	
	Amine	Oxidant	*T* [°C]	Time	**a**	**b**
1		$CuCl_2$	r.t.	1 h	**7a** (96%)	**7b** (2%)
2		$CuCl_2$	r.t.	24 h	**7a** (31%)	**7b** (47%)
3		$KMnO_4$	r.t.	24 h	**7a**[a]	**7b**[a]
4		$PDC/AgNO_3$	r.t.	3 d	**7a** (97%)	–
5		$KMnO_4/AgNO_3$	r.t.	24 h	**7a** (60%)	**7b** (20%)
1		$KMnO_4/AgNO_3$	r.t.	24 h	**7a** (60%)	**7b** (42%)
2		$KMnO_4/AgNO_3$	r.t.	24 h	**8a** (60%)	**8b** (31%)

[a] The major spot was identified as **7a** by TLC. A trace amount of **7b** also formed.

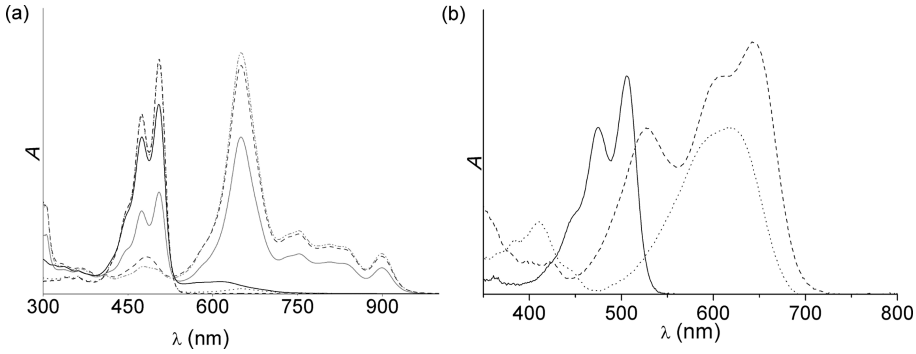


Figure 2. (a) Absorption profile for the progress of reaction of PMI diester **4** in pyrrolidine under an argon atmosphere (black dashes: 0 h, dark gray dots: 4 h, gray solid line: 20 h, gray dash dot dot: 21 h, dark gray dashes: 23 h, black solid line: vial opened). (b) Absorption of unsubstituted **4** (solid black), monopyrrolidyl **7a** (dot black), and dipyrroliydyl **7b** (dash black) PMI diesters.

reaction with the PDI, this reaction proceeds much faster in the presence of $CuCl_2$. Under copper catalysis, the reaction can either be stopped at a monosubstitution step or pushed further to the disubstituted product simply by controlling the reaction time. On the other hand, in the presence of PDC and $AgNO_3$ under argon, the reaction also led to the monosubstituted product **7a** in good yield and gave practically no disubstitution.

The absorption spectra for the reaction of PMI diester **4** and pyrrolidine under argon and the absorption spectra of the products after the exposure of the reaction mixture to ambient air are shown in Figure 2. The spectrum of the intermediate is similar to that observed for the diimide radical anion intermediate (Figure 1) and shows a distinct absorption in the near-IR region. Therefore, we suggest that the reaction also proceeds via a radical anion intermediate. The process does not necessarily require a catalyst, at least to obtain monosubstituted compounds (Table 2, Entry 3). However, the catalyst is needed for the preparation of disubstituted molecules in reasonable yields. The Cu-catalyzed reaction did not show the anion radical species by UV/Vis spectroscopy, most probably because of their fast oxidation upon formation.[19b] Silver nitrate alone may also serve as a catalyst for the amination. The results of the amination of PMI diester **4** are shown in Table 2.

Conclusions

We have found that the direct amination of peryleneimides proceeds as a stepwise substitution via a perylene radical anion and its subsequent oxidation. The substitution predominantly occurs regioselectively at the 1,6- and 7,12-positions of the bay region for perylenediimide and perylenemonoimide diester, respectively. The imide cycle directs the substitution to the distant position of the bay region; however, the presence of the imide is essential for the reaction to occur. The substitution occurs as a one-pot reaction with yields of 20–97% and can be controlled to produce selected products (mono or disubstituted perylenes) by variation of the oxidant.

Experimental Section

General: All commercially available reagents and solvents were purchased either from Sigma–Aldrich or from VWR and used without further purifications unless otherwise mentioned. The products were purified either by column chromatography with silica gel 60 (Merck) mesh size 40–63 μm or by preparative TLC with neutral aluminium oxide 60 F_{254} plates (Merck). The NMR spectra were recorded with a Varian Mercury 300 MHz spectrometer with tetramethylsilane (TMS) as the internal standard. HRMS measurements were performed with a Waters LCT Premier XE ESI-TOF bench-top mass spectrometer. Lock-mass correction (leucine enkephalin as reference compound), centering, and calibration were applied to the raw data to obtain accurate masses.

General Procedure for the Direct Amination of Peryleneimides: Silver nitrate (1–10 equiv.) was added to a stirred solution of peryleneimide (1 equiv.) in the amine (1.5–5 mL), and the mixture was stirred for 10 min. Powdered $KMnO_4$ (1–10 equiv.) was added to this reaction mixture in portions over a period of 30 min, and stirring was continued for another 16 h. On completion, the reaction mixture was concentrated under reduced pressure, and the residue was dissolved in chloroform (20 mL). The organic phase was washed with water (2× 50 mL) and dried with Na_2SO_4, and the solvents were evaporated. The crude product was purified by TLC (neutral aluminum oxide 60 F_{254} TLC plates with dichloromethane as eluent) to yield the pure compound.

2,9-Dioctylisoquinolino[4′,5′,6′:6,5,10]anthra[2,1,9-*def*]isoquinoline-1,3,8,10(2*H*,9*H*)-tetrone (1) and 2,9-Bis(2,5-di-*tert*-butylphenyl)-isoquinolino[4′,5′,6′:6,5,10]anthra[2,1,9-*def*]isoquinoline-1,3,8,10(2*H*,9*H*)-tetrone (1′): Compounds **1** and **1′** were prepared from perylenetetracarboxylic anhydride (PTCDA) according to the literature procedure described by Langhals.[20]

Tetrabutyl Perylene-3,4,9,10-tetracarboxylate (2) and Dibutyl 1,3-Dioxo-1*H*,3*H*-benzo[5,10]anthra[2,1,9-*def*]isochromene-8,9-dicarboxylate (3): These compounds were prepared from perylenetetracarboxylic anhydride (PTCDA) according to the procedure described by Wang et al.[18g]

Dibutyl 2-Octyl-1,3-dioxo-2,3-dihydro-1*H*-benzo[5,10]anthra[2,1,9-*def*]isoquinoline-8,9-dicarboxylate (4): A mixture of **3** (0.193 mmol, 101 mg), imidazole (1.0 g), and *n*-octylamine (1.15 mmol, 191 μL) was stirred at 140 °C for 4 h. On completion, the reaction mixture was cooled to 60 °C, and ethanol (5 mL) was added. The mixture was neutralized by the dropwise addition of HCl (2 M) and extracted with toluene (three times). The organic phase was washed

with water (twice), dried with Na_2SO_4, and concentrated. The crude product was purified through silica gel with dichloromethane as the eluent to yield **4** (83 mg, 68%) as a dark red solid. ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 8.36–8.39 (d, J = 7.92 Hz, 2 H), 8.13 (t, J = 8.50 Hz, 4 H), 7.95–7.97 (d, J = 7.92 Hz, 2 H), 4.36 (t, J = 6.74 Hz, 4 H), 4.16 (t, J = 7.62 Hz, 2 H), 1.67–1.94 (m, 6 H), 1.20–1.64 (m, 15 H), 1.02 (t, J = 7.33 Hz, 6 H), 0.88 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 168.44, 163.58, 135.24, 132.04, 132.00, 131.27, 130.39, 129.24, 129.03, 128.99, 122.59, 125.83, 122.16, 121.77, 65.81, 56.56, 40.80, 32.08, 30.86, 29.60, 29.51, 28.37, 27.45, 22.89, 19.51, 14.36, 14.06, 9.60, 0.23 ppm. HRMS (ESI-TOF): calcd. for $C_{40}H_{43}NO_6$ $[M]^+$ 633.3085; found 633.3068.

2,9-Dioctyl-5-(pyrrolidin-1-yl)isoquinolino[4′,5′,6′:6,5,10]anthra-[2,1,9-*def*]isoquinoline-1,3,8,10(2*H*,9*H*)-tetrone (5a): Pyrrolidine (20 mL) was bubbled with argon for 5 min, and **1** (0.0138 mmol, 8.5 mg) was added. The resultant mixture was again purged with argon for 1 min and heated at 60 °C for 5 h. A pyridinium dichromate solution (0.138 mmol, 5.3 mg dissolved in pyrrolidine and purged with argon for 5 min) was added to the reaction mixture, which was then stirred for 5 min. The reaction was quenched with water (20 mL), extracted with chloroform (three times), dried with Na_2SO_4, and concentrated. The crude product was purified by TLC (neutral aluminum oxide 60 F_{254} TLC plates with dichloromethane as eluent) to yield **5a** as a green solid (7.2 mg, 70%). ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 8.57–8.64 (m, 2 H), 8.29–8.49 (m, 4 H), 7.39–7.57 (m, 1 H), 4.09–4.31 (m, 4 H), 3.58–3.83 (m, 2 H), 2.74 (br s, 2 H), 1.88–2.23 (m, 4 H), 1.65–1.86 (m, 4 H), 1.23–1.52 (m, 21 H), 0.88 (t, J = 6.74 Hz, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 163.87, 163.81, 163.71, 163.65, 148.40, 135.42, 135.18, 132.59, 130.95, 130.68, 128.93, 128.59, 127.11, 124.19, 126.56, 123.68, 122.98, 122.56, 122.33, 121.62, 120.41, 118.96, 115.83, 52.42, 40.67, 40.58, 31.86, 31.85, 29.42, 29.37, 29.28, 29.25, 28.18, 27.24, 27.18, 25.78, 22.66, 14.12 ppm. HRMS (ESI-TOF): calcd. for $C_{44}H_{49}N_3O_4$ $[M]^+$ 683.3718; found 683.3740.

2,9-Dioctyl-5,13-di(pyrrolidin-1-yl)isoquinolino[4′,5′,6′:6,5,10]-anthra[2,1,9-*def*]isoquinoline-1,3,8,10(2*H*,9*H*)-tetrone (5b): The compound was prepared by following the general procedure for the direct amination of peryleneimides. Compound **1** (0.0325 mmol, 20 mg) was stirred with silver nitrate (0.0516 mmol, 8.7 mg) in pyrrolidine (5 mL). Powdered $KMnO_4$ (0.0516 mmol, 8.2 mg) was added to the reaction mixture, which was then stirred for 24 h to afford **5b** (65%, 15.8 mg) as a dark blue solid. ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 8.68 (d, J = 7.92 Hz, 2 H), 8.34 (s, 2 H), 7.86 (d, J = 8.21 Hz, 2 H), 4.13–4.36 (m, 4 H), 3.56–3.91 (m, 4 H), 2.77 (br s, 3 H), 1.87–2.23 (m, 8 H), 1.67–1.86 (m, 4 H), 1.13–1.53 (m, 30 H), 0.87 (t, J = 6.74 Hz, 9 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 164.65, 164.35, 150.24, 135.94, 131.28, 130.45, 128.73, 128.47, 123.52, 123.11, 117.99, 117.80, 117.19, 117.10, 52.40, 40.87, 40.69, 32.09, 32.06, 29.93, 29.68, 29.59, 29.49, 29.46, 28.49, 28.44, 27.49, 27.38, 25.90, 22.89, 14.34 ppm. HRMS (ESI-TOF): calcd. for $C_{48}H_{56}N_4O_4$ $[M]^+$ 752.4296; found 752.4291.

2,9-Bis(2,5-di-*tert*-butylphenyl)-5,13-di(pyrrolidin-1-yl)isoquinolino-[4′,5′,6′:6,5,10]anthra[2,1,9-*def*]isoquinoline-1,3,8,10(2*H*,9*H*)-tetrone (5b′): The general procedure for the direct amination was followed by stirring **1′** (0.026 mmol, 20 mg), $AgNO_3$ (0.26 mmol, 44 mg), and powdered $KMnO_4$ (0.26 mmol, 41 mg) in pyrrolidine (3 mL) for 24 h at room temperature to give **5b′** (69%, 16.3 mg) as a dark blue solid. ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 8.76 (d, J = 8.21 Hz, 2 H), 8.41 (s, 2 H), 7.92 (dd, J = 8.21 Hz, 2 H), 7.63–7.59 (m, 2 H), 7.49–7.44 (m, 2 H), 7.03–7.00 (m, 2 H), 3.77 (br, 3 H), 2.86 (br, 3 H), 2.05 (br, 8 H), 1.36–1.33 (m, 36 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 165.38, 165.17, 150.08, 150.03, 150.01, 149.95, 143.88, 143.86, 136.05, 136.03, 133.59, 133.56, 132.96, 132.93, 131.45, 130.93, 130.67, 128.87, 128.83, 128.73, 128.68, 127.79, 127.67, 126.19, 126.01, 123.34, 123.24, 118.08, 117.93, 117.36, 117.12, 52.21, 35.58, 35.56, 34.23, 31.86, 31.83, 31.25, 31.23, 29.69, 25.72 ppm. HRMS (ESI-TOF): calcd. for $C_{60}H_{64}N_4O_4$ $[M]^+$ 904.4922; found 904.4949.

2,9-Bis(2,5-di-*tert*-butylphenyl)-5,13-di(piperidin-1-yl)isoquinolino-[4′,5′,6′:6,5,10]anthra[2,1,9-*def*]isoquinoline-1,3,8,10(2*H*,9*H*)-tetrone (6b′): The general procedure for the direct amination was followed by stirring **1′** (0.013 mmol, 10 mg), $AgNO_3$ (0.13 mmol, 22 mg), and powdered $KMnO_4$ (0.13 mmol, 21 mg) in piperidine (1.5 mL) for 24 h at room temperature to give **6b′** (60%, 7.3 mg) as a dark blue solid. ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 9.81 (d, J = 8.50 Hz, 2 H), 8.68 (d, J = 8.50 Hz, 2 H), 8.46 (s, 2 H), 7.62–7.59 (m, 2 H), 7.49–7.44 (m, 2 H), 7.02–6.98 (m, 2 H), 3.48–3.38 (m, 4 H), 2.98–2.87 (m, 4 H), 1.92–1.74 (m, 12 H), 1.35–1.32 (m, 36 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 164.80, 164.69, 153.45, 150.09, 150.01, 143.91, 143.82, 136.42, 136.39, 133.21, 132.74, 132.09, 131.17, 129.35, 128.77, 128.72, 128.30, 127.74, 127.58, 126.26, 126.15, 123.87, 123.57, 123.46, 122.86, 121.16, 120.58, 53.20, 53.08, 35.56, 34.25, 33.70, 31.93, 31.83, 31.25, 31.23, 30.16, 29.71, 29.37, 26.70, 25.87, 23.77, 22.70 ppm. HRMS (ESI-TOF): calcd. for $C_{62}H_{68}N_4O_4$ $[M]^+$ 932.5235; found 932.5287.

Dibutyl 2-Octyl-1,3-dioxo-6-(pyrrolidin-1-yl)-2,3-dihydro-1*H*-benzo-[5,10]anthra[2,1,9-*def*]isoquinoline-8,9-dicarboxylate (7a) and Dibutyl 2-Octyl-1,3-dioxo-6,11-di(pyrrolidin-1-yl)-2,3-dihydro-1*H*-benzo[5,10]anthra[2,1,9-*def*]isoquinoline-8,9-dicarboxylate (7b): The general procedure for the direct amination was followed by stirring **4** (0.0946 mmol, 60 mg), $AgNO_3$ (0.945 mmol, 160 mg), and powdered $KMnO_4$ (0.945 mmol, 150 mg) in pyrrolidine (1.5 mL) for 24 h at room temperature to give **7a** (40 mg, 60%) and **7b** (14.2 mg, 20%) as dark solids.

Data for 7a: ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 8.68–8.49 (m, 2 H), 8.46–8.27 (m, 2 H), 8.00 (s, 1 H), 7.95 (d, J = 8.05 Hz,1 H), 7.15 (d, J = 8.05 Hz, 1 H), 4.44–4.29 (m, 4 H), 4.26–4.16 (m, 2 H), 3.83–3.67 (m, 2 H), 3.67–3.61 (m, 2 H), 2.87–2.65 (m, 2 H), 2.18–2.00 (m, 2 H), 2.00–1.88 (m, 2 H), 1.87–1.69 (m, 6 H), 1.60–1.39 (m, 8 H), 1.39–1.21 (m, 10 H), 1.02 (t, J = 7.24 Hz, 3 H), 0.98 (t, J = 7.24 Hz, 3 H), 0.91–0.84 (m, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 169.07, 168.10, 164.29, 164.16, 147.91, 136.52, 131.43, 131.26, 131.15, 131.02, 130.46, 129.26, 127.03, 126.17, 123.47, 122.69, 121.96, 120.73, 119.60, 117.58, 111.76, 70.77, 65.72, 65.66, 52.73, 40.68, 32.09, 30.92, 30.82, 29,92, 29.66, 29.50, 28.43, 27.48, 25.93, 22.89, 19.50, 19.48, 14.34, 14.06, 14.04 ppm. HRMS (ESI-TOF): calcd. for $C_{44}H_{50}N_2O_6$ $[M]^+$ 702.3663; found 702.3704.

Data for 7b: ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 8.65 (t, J = 7.92 Hz, 2 H), 7.83 (s, 2 H), 7.51 (t, J = 7.92 Hz, 2 H), 4.33 (t, J = 7.04 Hz, 4 H), 4.24 (t, J = 7.33 Hz, 2 H), 3.90–3.50 (m, 4 H), 3.02–2.52 (m, 4 H), 1.84–1.71 (m, 6 H), 1.55–1.40 (m, 8 H), 0.99 (t, J = 7.33 Hz, 6 H), 0.93–0.79 (m, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 168.65, 164.57, 149.95, 136.62, 132.95, 131.30, 130.34, 128.61, 128.46, 122.89, 116.45, 116.34, 115.89, 112.60, 65.63, 52.61, 40.61, 32.11, 30.88, 29.93, 29.70, 29.51, 28.52, 27.51, 25.97, 22.89, 19.49, 14.35, 14.07 ppm. HRMS (ESI-TOF): calcd. for $C_{48}H_{57}N_3O_6$ $[M]^+$ 771.4242; found 771.4203.

Dibutyl 2-Octyl-1,3-dioxo-6-(piperidin-1-yl)-2,3-dihydro-1*H*-benzo-[5,10]anthra[2,1,9-*def*]isoquinoline-8,9-dicarboxylate (8a) and Dibutyl 2-Octyl-1,3-dioxo-6,11-di(piperidin-1-yl)-2,3-dihydro-1*H*-benzo[5,10]anthra[2,1,9-*def*]isoquinoline-8,9-dicarboxylate (8b): The general procedure for the direct amination was followed by stirring **4** (0.0.032 mmol, 20.5 mg), $AgNO_3$ (0.32 mmol, 53 mg), and powdered $KMnO_4$ (0.32 mmol, 50 mg) in piperidine (3 mL) for 24 h at

room temperature to give **8a** (15 mg, 64%) and **8b** (8 mg, 31%) as dark solids.

Data for 8a: ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 9.29 (d, J = 8.21 Hz, 2 H), 8.54–8.46 (m, 2 H), 8.29 (d, J = 7.92 Hz, 2 H), 8.00 (s, 1 H), 7.94 (d, J = 7.92 Hz, 1 H), 4.38–4.31 (m, 4 H), 4.22 (t, J = 7.33 Hz, 2 H), 3.41–3.37 (m, 2 H), 2.97–2.89 (m, 2 H), 1.85–1.71 (m, 11 H), 1.57–1.25 (m, 20 H), 1.03–0.07 (m, 6 H), 0.90–0.85 (m, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 168.91, 168.32, 164.16, 163.83, 151.31, 137.11, 136.16, 131.90, 131.74, 131.71, 131.57, 131.53, 131.17, 129.26, 129.06, 127.71, 126.89, 124.44, 124.27, 123.53, 123.17, 121.39, 120.51, 119.82, 118.4, 65.75, 65.68, 52.80, 40.70, 32.08, 30.90, 30.80, 29.93, 29.63, 29.48, 28.42, 27.45, 25.93, 24.08, 22.88, 19.49, 14.33, 14.05 ppm. HRMS (ESI-TOF): calcd. for $C_{45}H_{52}N_2O_6Na$ $[M + Na]^+$ 739.3718; found 739.3747.

Data for 8b: ^{1}H NMR (300 MHz, $CDCl_3$, TMS): δ = 9.39 (d, J = 8.21 Hz, 2 H), 8.58 (d, J = 8.21 Hz, 2 H), 7.85 (s, 2 H), 4.34 (t, J = 7.04 Hz, 4 H), 4.23 (t, J = 7.62 Hz, 2 H), 3.35–3.31 (m, 4 H), 2.90–2.82 (m, 4 H), 1.82–1.72 (m, 16 H), 1.51–1.43 (m, 7 H),1.28–1.25 (m, 15 H), 1.01 (t, J = 7.33 Hz, 6 H), 0.90–0.85 (m, 4 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, TMS): δ = 168.66, 164.15, 152.31, 137.36, 134.14, 131.66, 131.02, 129.02, 128.2, 123.12, 121.22, 119.77, 119.4, 119.06, 65.66, 53.06, 40.63, 32.09, 30.82, 29.92, 29.65, 29.48, 28.47, 27.48, 25.99, 24.16, 22.88, 19.47, 14.33, 14.03 ppm. HRMS (ESI-TOF): calcd. for $C_{50}H_{61}N_3O_6$ $[M]^+$ 799.4555; found 799.4553.

Supporting Information (see footnote on the first page of this article): NMR spectra of all the compounds synthesized for the current work.

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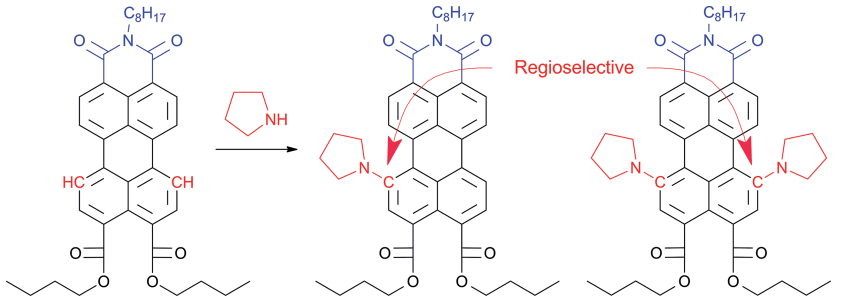
Polycycles



An efficient and direct protocol for the highly regioselective amination of perylene-imides has been developed. The method involves the stepwise formation of a radical anion, which is then oxidized in situ under mild reaction conditions.

Keywords: Amination / Perylenes / Polycycles / Regioselectivity / Radical anions / Imides

