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π-Extension of Strained Benzenoid Macrocycles Using the Scholl Reaction

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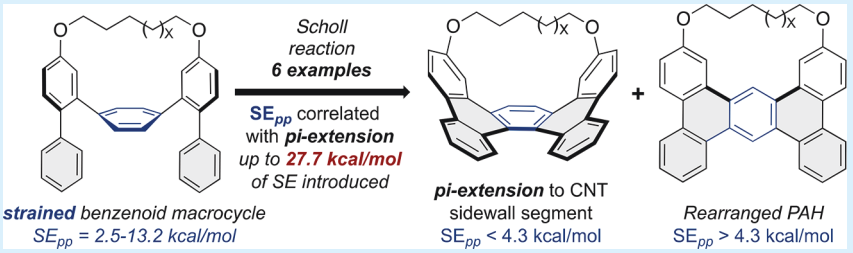
Supporting Information



ABSTRACT: A series of bent *p*-terphenyl-containing macrocycles have been synthesized and then regioselectively brominated, arylated, and subsequently subjected to a Scholl-based cyclodehydrogenation reaction. Shortening the alkyloxy bridging unit of these macrocycles increases the bend in the *p*-terphenyl unit, as well as the strain energy (SE) of the central *para*-phenylene ring system. For the first time, incremental increases in SE of the macrocyclic structure of this class of benzenoid compounds have been investigated in the context of π-extension to strained polycyclic aromatic hydrocarbon systems using the Scholl reaction.

The synthesis of polycyclic aromatic hydrocarbons (PAHs) from substituted benzenoid systems, using a cyclodehydrogenation (Scholl) reaction protocol, has proven to be somewhat unpredictable.[1] Regioisomeric products that result from undesired and, in some cases, nonobvious cyclization modes have been reported.[2] For example, Durola and coworkers observed that 2,2″-bis(4-*tert*-butylphenyl)-*p*-terphenyl (**1**) undergoes a cyclodehydrogenation reaction in the presence of iron(III) chloride to afford [5]helicene **3** in preference to **2** (Scheme 1A).[3] Despite the crowded and congested transition state that must be attained to furnish the twisted PAH **3**, the *cisoid* mode of cyclization proved to be major. A similar annulation reaction was computationally investigated by Hilt and co-workers,[4] who showed that the preferred, congested mode of cyclization can be attributed to the uneven distribution of orbital coefficients about the central ring (after a single annulation), with the site of the second annulation reaction exhibiting a larger orbital coefficient. In the absence of the bulky *tert*-butyl groups, formation of a carbon−carbon bond across the bay region of **3** is possible to form PAHs such as **4**.[2] If this type of annulation reaction could be called upon to convert a nonplanar benzenoid macrocyclic system into a nonplanar PAH-containing macrocycle, it would represent a viable π-extension strategy for the synthesis of carbon nanotube (CNT) sidewall segments. In the context of an [*n*]cycloparaphenylene ([*n*]CPP), connecting adjacent arene vertices of the nanohoop backbone to arene vertices of appended phenyl or aryl substituents would provide entry to carbon nanobelts (CNBs).[5] The latter would provide entry to size-selective and structurally uniform armchair CNTs using programmed or controlled C−C bond-forming reactions.[6]

Several groups have attempted to use the Scholl reaction to stitch together substituent aromatic rings to backbone arene units within the macrocyclic framework of [*n*]CPPs; however, these efforts have been met with limited success. Müllen and coworkers have reported the successful synthesis of a hexabenzocoronene (HBC)-incorporated [21]CPP via the introduction of strategically placed methyl groups at *para*-phenylene units within the macrocyclic backbone of a [21]CPP (SE$_{pp}$ = 1.3 kcal/mol) derivative to circumvent 1,2-phenyl shifts.[7] The application of this strategy to a homologous, but more strained, [15]CPP (SE$_{pp}$ = 2.7 kcal/mol) failed to produce the HBC-incorporated macrocycle. Similarly, a polyphenylated [9]CPP (SE$_{pp}$ = 7.4 kcal/mol) derivative did not undergo π-extension when subjected to Scholl reaction conditions.[8] Jasti and coworkers have investigated a Scholl-based annulation protocol for the π-extension of arylated [12]CPP and [8]CPP (SE$_{pp}$ = 9.2 kcal/mol) derivatives; however, only mixtures of isomeric macrocycles and ring-opened products were obtained.[9] Although these studies have demonstrated that direct π-extension of nonplanar benzenoid systems to strained PAH systems using a cyclodehydrogenation reaction is challenging, they are limited to only a few arene-substituted CPPs. As such, an investigation to explore the usefulness of this strategy and its potential limitations was designed using a series of polyarylated *p*-terphenyl-containing macrocycles (Scheme 1B). The central *para*-phenylene, which is bent, allows for a detailed analysis of how strain affects the desired annulation and to what extent pre-

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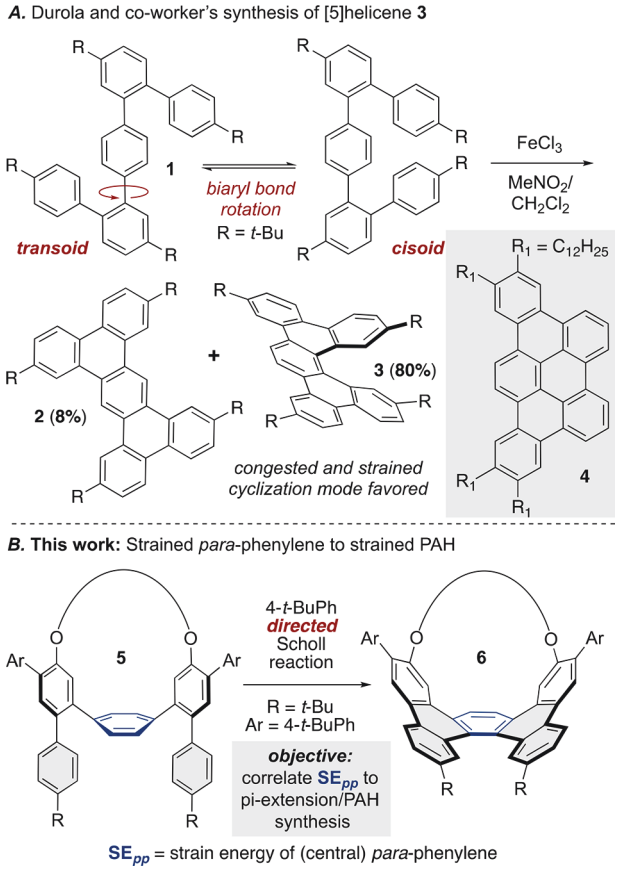
Scheme 1. π-Extension of Congested *p*-Terphenyls

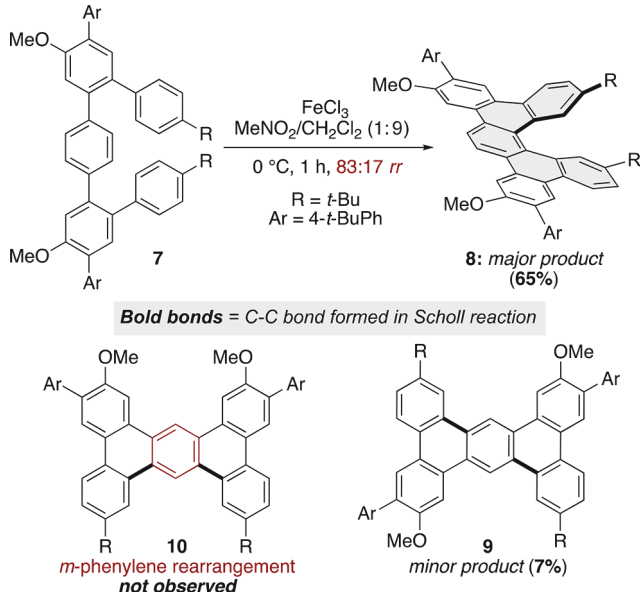


existing and bent π-systems can be extended using this methodology.

Inspired by the work of Durola and co-workers,[3] we sought to exploit the 4-*tert*-butylphenyl group as the arene unit for π-extension at the bent *p*-terphenyl system of **6** (Scheme 1B). To ensure that the introduction of electron-rich arene units within the *p*-terphenyl unit does not lead to undesired, unwanted, or uncontrollable rearrangement reactions, which have been observed by others,[10] a non-macrocyclic homologue of **5** was synthesized.[11] Indeed, treatment of **7** with 8.0 equiv of iron(III) chloride as a solution in 1:9 nitromethane/dichloromethane led to the formation of [5]helicene **8** in 65% yield and tetrabenz(*a*,*c*,*h*,*j*)anthracene (*transoid* cyclization) derivative **9** in 7% yield (83:17 rr, Scheme 2). The formation of **10**, which is the result of *para*- to *meta*-phenylene rearrangement, followed by cyclodehydrogenation, was not observed.

A four-stage, six-step synthetic protocol for the preparation of bent *p*-terphenyl-containing macrocycles with alkyloxy bridging units of 4−8 atoms was developed in our laboratory.[12] This strategy was used to synthesize four new homologues (n = 9−12) for the present study.[13] Only homologues that do not succumb to protic acid-mediated rearrangements were subjected to these investigations (SE_{pp} = 2.5−13.2 kcal/mol).[12b] Regioselective bromination of **11**−**16** was accomplished by heating a bromine solution of these macrocycles in *ortho*-dichlorobenzene at 80 °C for 3−12 h. Tetrabromides **17**−**22** were afforded in 80−95% yield as the sole products of these reactions. A four-fold Suzuki cross-coupling reaction of **17**−**22** with 4-*tert*-butylphenylboronic acid proceeded in high yield (70−92%) to furnish six arylated precursors for the Scholl reaction study. Employing the same reaction conditions that led

Scheme 2. Scholl-Based π-Extension Reaction of Model *p*-Terphenyl



to the successful synthesis of helicene **8** to **23**−**25** gave a single PAH-containing macrocycle in 80−90% yield. The ^{1}H NMR spectra of the PAH produced from the Scholl reactions of **23**−**25** showed nine aromatic signals, with a pair of low-field singlets at ∼9.5 and 9.2 ppm. This pointed to the structure of tetrabenz(*a*,*c*,*h*,*j*)anthracene-containing macrocycles **29B**, **30B**, and **31B**, which would result from a 1,2-aryl shift reaction at some point along the reaction pathway. The desired *cisoid* π-extension product would produce only eight aromatic signals in the ^{1}H NMR spectra of **29A**−**31A**, as well as a shielded singlet for the *tert*-butyl protons of the desired helicene (see Supporting Information (SI)). The PAH structures of **29B**−**31B** were ultimately confirmed to be that of tetrabenz(*a*,*c*,*h*,*j*)anthracene **10** when a BBr_3-mediated cleavage of the alkyloxy bridging unit of **29B**, followed by methylation of the resulting diol, produced a PAH that was virtually identical to that of **8** (Scheme 2) with the exception of two low-field (bay region) singlets at 10.00 and 9.73 ppm (see SI for details).

At this juncture, homologues containing a central *para*-phenylene unit with greater than 4.9 kcal/mol of SE led only to the formation of tetrabenz(*a*,*c*,*h*,*j*)anthracene-containing macrocycles. The remaining three homologues, **26**−**28**, contain longer alkyloxy bridging units and thus less strained *para*-phenylene rings (SE_{pp} = 2.5−4.3 kcal/mol). Subjecting macrocycles **27** (SE_{pp} = 3.0 kcal/mol) and **28** (SE_{pp} = 2.5 kcal/mol) to the Scholl reaction conditions described above resulted in the formation of desired annulation products **33A** and **34A** as single regioisomers in 80% yield (Scheme 3). No rearrangement or *transoid* cyclization was observed for these homologues. In the case of arylated macrocycle **26** (SE_{pp} = 4.3 kcal/mol), π-extension to afford the desired PAH-containing macrocycle **32A** takes place; however, it is accompanied by the formation **32B**. The ratio of annulation products was determined to be 83:17 (^{1}H NMR analysis) in favor of the rearranged isomer. Nonetheless, regioisomeric macrocycles **32A** (9%) and **32B** (43%) could be separated and characterized. To test the stability of **32A**, it was resubjected to identical reaction conditions under which it was formed. No decomposition or subsequent rearrangement was observed, and **32A** was quantitatively recovered.

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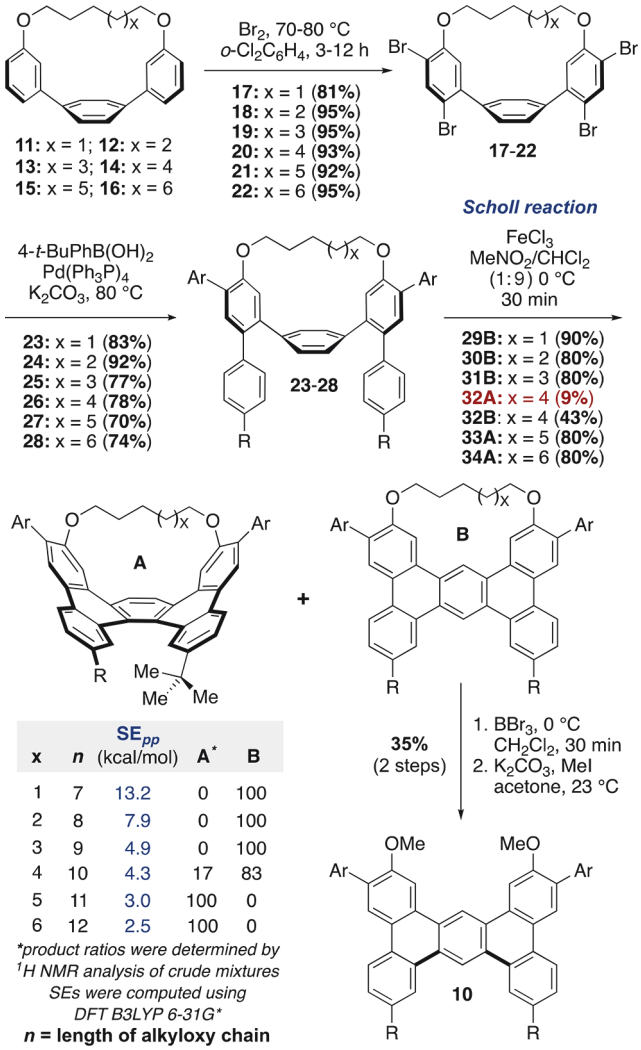
Scheme 3. Synthesis of Arylated Macrocycles 23−28 and an Investigation of Their Scholl Reactions



x	n	SE_{pp} (kcal/mol)	A*	B
1	7	13.2	0	100
2	8	7.9	0	100
3	9	4.9	0	100
4	10	4.3	17	83
5	11	3.0	100	0
6	12	2.5	100	0

*product ratios were determined by ^{1}H NMR analysis of crude mixtures
SEs were computed using DFT B3LYP 6-31G*
n = length of alkyloxy chain

All attempts to grow crystals suitable for X-ray crystallographic analysis of **32A** were unsuccessful. However, an optimized geometry was obtained using density functional theory calculations with the B3LYP functional and 6-31G* basis set (Figure 1). The structure of **32A** is both twisted and bent due to the presence of the [5]helicene moiety and the octyloxy group bridging the PAH structure, respectively. The end-to-end bend of the dibenzo[*f,j*]picene unit of **32A** is 31.8°, and the SE of this π-system is 46.9 kcal/mol. The former was calculated by measuring the angle between the two most distant carbon atoms of the PAH and the centroid of the central aromatic ring of **32A** (Figure 1). The latter was obtained by using a method previously reported by Höger, Grimme, and co-workers.[14] Upon annulation about the bent *p*-terphenyl backbone of **26**, 27.7 kcal/mol of SE is introduced into the macrocyclic structure of **32A** (SE(**26**) = 19.2 kcal/mol). The torsional twist angle (θ) of the dibenzo[5]helicene unit is 23.3°, which is smaller than θ (25.1°) for the unperturbed dibenzo[5]helicene **8**.[15] Bending the dibenzo[5]helicene unit of **32A** compresses the angle θ and brings the *tert*-butyl groups closer together, which should raise the activation barrier for the annulation reaction of **26** and related homologues, relative to that of **8**. The distance between the fjord region carbon atoms for **32A** is only slightly smaller than that of **8** (cf. 3.03−3.04 Å). The absorption spectra for **8** and **32A** show four absorption bands with λ_{max} of 365 and 368 nm, respectively (Figure 2). Unlike other bent PAHs, which are typically blue-shifted relative to the unperturbed, planar compound, the dibenzo[*f,j*]picene, or dibenzo[5]helicene, unit of **32A** is only slightly red-shifted. Time-dependent DFT calculations (B3LYP/6-31G* level of theory) predict a red shift in the electronic absorption spectra of **32A** relative to that of **8**, with λ_{max} of 351 and 345 nm, respectively. The fluorescence spectra of **32A** and **8** show two emission bands with a λ_{max} of 438 nm for both compounds. The fluorescence quantum yields (emission efficiencies) of **32A** and **8** were measured to be 0.25 and 0.12, respectively. The increased emission efficiency of **32A** is likely due to constraints imposed by the alkyloxy bridging unit, which makes for a more ridged dibenzo[5]helicene fluorophore. To the best of our knowledge, **32A** is the first example of a bent analogue of this PAH, and it appears that bending an already twisted PAH unit does not have a pronounced effect on the photophysical properties of dibenzo[*f,j*]picene.

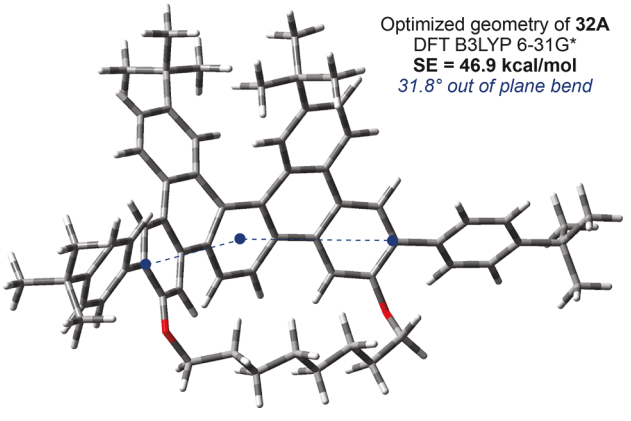


Figure 1. Optimized geometry of **32A** (DFT-B3LYP 6-31G*).

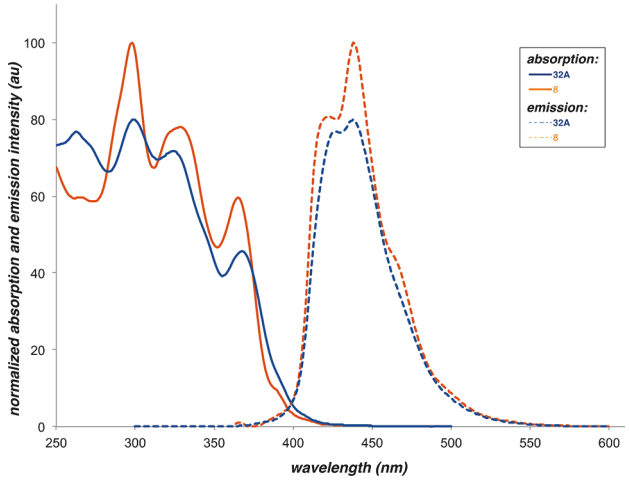


Figure 2. UV−vis and fluorescence spectra of **32A** (blue, 2.0×10^{-5} M) and **8** (orange, 5.0×10^{-6} M). Fluorescence spectra were measured with 365 nm excitation.

In conclusion, a series of bent *p*-terphenyl-containing macrocycles have been synthesized and regioselectively arylated. For the first time, successful annulation onto a strained *para*-phenylene unit using the Scholl reaction has been correlated to the SE of the *para*-phenylene ring (SE_{pp}). Furthermore,

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intermediates that result from rearrangement reactions under these π-extension conditions have been unequivocally identified and characterized. These studies suggest that π-extension of bent *para*-phenylene units is possible when the SE_{pp} is less than 4.3 kcal/mol. When the SE*pp* is less than 3.0 kcal/mol, no rearrangement is observed. The structure of **32A** represents a rare example of a macrocyclic helicene system that is both twisted and bent, with an end-to-end bend angle of 31.8° and 46.9 kcal/mol (an additional 27.7 kcal/mol starting from **26**) of SE. We hope that these results will serve as a guide for future synthetic efforts aimed toward π-extension of benzenoid macrocycles and their conversion into PAH-containing macrocycles, such as CNBs. Finally, mechanistic investigations of the Scholl reactions presented here to better understand the observed rearrangement reactions, as well as the synthesis of analogues of **32A**, are underway in our laboratory and will be reported in due course.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b02979.

Experimental procedures, characterization data, including ^{1}H and ^{13}C NMR spectra for all new compounds, and crystallographic data (PDF)

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Notes

The authors declare no competing financial interest.

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(11) For the synthesis of **7**, see Scheme SI-2 in the Supporting Information.

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(13) For details, see Scheme SI-1 in the Supporting Information.

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