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Selective Synthesis of Strained [7]Cycloparaphenylene: An Orange-Emitting Fluorophore

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S Supporting Information

ABSTRACT: [*n*]Cycloparaphenylenes, which are short fragments of carbon nanotubes, have unique size-dependent optical properties. In this communication, we describe the first synthesis of [7]cycloparaphenylene ([7]CPP), the smallest cycloparaphenylene prepared to date. In order to access this structure, we have developed a synthetic route that capitalizes on successive orthogonal Suzuki–Miyaura coupling reactions. [7]CPP has 83 kcal/mol of strain energy and an orange emission at 592 nm.

The cycloparaphenylene (CPP) class of molecules represents the smallest possible slice of an armchair carbon nanotube (CNT).[1−3] The syntheses of these strained sp^2-hybridized molecules have received significant attention recently because of their potential application as templates for the preparation of single-chirality CNTs.[4−10] In addition to their potential utility in CNT synthesis, CPPs exhibit size-dependent optical properties (Figure 1). All synthesized CPPs possess a common absorption maximum, but their fluorescence is conditional on size. For example, [12]-CPP has an absorption maximum at 340 nm with a fluorescence maximum at 450 nm.[4] Interestingly, [8]CPP also absorbs light at 340 nm, but its emission is red-shifted dramatically, with a maximum at 540 nm.[6,10] This trend of red-shifted fluorescence corresponding to smaller size is unusual in that it is the opposite of the typical "particle in a box" phenomenon seen in semiconductor quantum dots[11] and linear *p*-phenylenes.[12] As in the case of quantum dots, this ability to absorb at similar wavelengths yet size-selectively emit at various wavelengths is a property that could be exploited for multiple applications, such as biological imaging.[13,14] In order to probe the size-dependent optical properties of CPPs further, synthetic access to smaller versions is necessary. Herein we report the first synthesis and characterization of highly strained [7]cycloparaphenylene, the smallest CPP that has been prepared to date.

The first synthesis of a cycloparaphenylene was reported by Jasti and Bertozzi in 2009.[4] The synthetic approach relied on cyclohexadiene structures as masked benzene rings (**1** and **2** in Figure 2).[15] In a "shotgun"-type approach, aryl halide **1** and boronate **2** were subjected to Suzuki–Miyaura coupling conditions, leading to macrocycles **3**, **4**, and **5**. These three macrocycles were subsequently converted to [9]-, [12]-, and [18]CPP, respectively. Notably, the more strained precursor to [6]CPP was not formed in the macrocyclization step, likely because of the increased strain energy of a macrocycle with only two cyclohexadiene moieties. Since this pioneering report, Itami has synthesized several cycloparaphenylene structures utilizing a cyclohexane unit (**6**) as the masked aromatic ring.[5,7−9] Again, the smallest structure prepared through this method is [9]CPP.[9] [8]CPP, the smallest CPP previously synthesized, was reported by Yamago.[6,10] With 73 kcal/mol of strain energy, this structure was prepared through square-planar platinum complex **7**, which underwent reductive elimination to deliver [8]CPP. A synthetic strategy to access even smaller cycloparaphenylenes would be a significant addition to this emerging field.

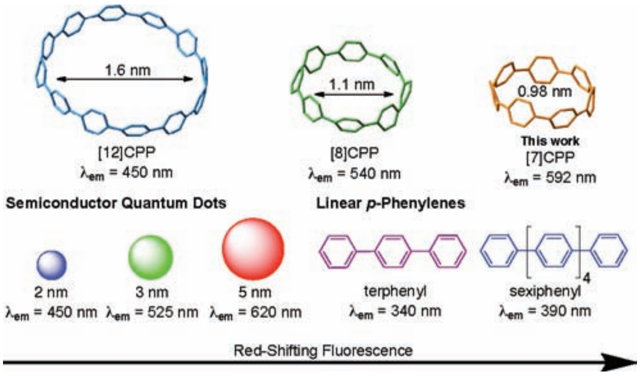

Figure 1. Size-dependent fluorescence of cycloparaphenylenes, quantum dots, and linear *p*-phenylenes.

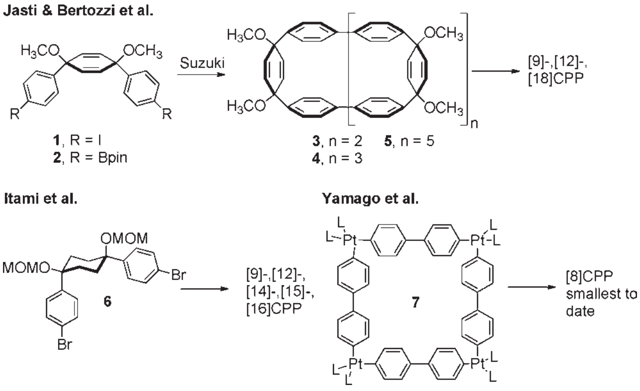

Figure 2. Previous synthetic routes are not amenable to smaller CPPs.

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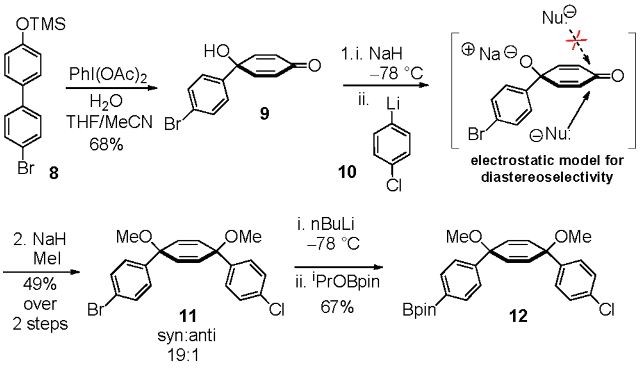
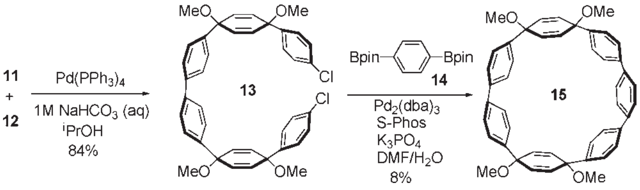
Scheme 1. Preparation of Monomers 11 and 12



Scheme 2. Orthogonal Suzuki−Miyaura Coupling Reactions To Prepare Strained Macrocycle 15



Our synthetic strategy to [7]CPP relies on orthogonal Suzuki−Miyaura coupling reactions (see Scheme 2). The synthesis of key fragments **11** and **12** is shown in Scheme 1. Silyl-protected bromophenol **8** underwent oxidative dearomatization in the presence of H_2O to generate ketone **9** in 68% yield.[16] Deprotonation of alcohol **9** with sodium hydride followed by addition of aryllithium **10** and subsequent methylation yielded dimethyl ether **11** in a diastereomeric ratio of 19:1 favoring the syn product. Interestingly, when alcohol **9** was alternatively treated with 2 equiv of aryllithium **10** (presumably proceeding through the lithium alkoxide), the dr was lower (10:1). When alcohol **9** was methylated before the addition of the aryl nucleophile, the diastereoselectivity of the reaction dropped precipitously to 3:1. This sense of stereoselectivity is consistent with an electrostatic model in which the anionic nucleophile approaches from the opposite face of the existing negative charge (Scheme 1).[17] Simply put, the more ionic the bond (NaO > LiO > CH_3O), the greater the diastereoselectivity of the reaction. To prepare for a Suzuki−Miyaura coupling, a portion of **11** was converted to boronate **12** through lithium−halogen exchange followed by subsequent trapping of the reactive species with (isopropoxy)pinacolborane.

With fragments **11** and **12** in hand, macrocycle **15** was assembled utilizing orthogonal Suzuki−Miyaura coupling reactions (Scheme 2). Selective coupling of **11** and **12** using tetrakis(triphenylphosphine)palladium as the catalyst yielded dichloride **13** in 84% yield.[18] As expected, the aryl chloride functionality remained intact under these conditions, preventing the formation of larger oligomeric structures. When a more reactive ligand system (Buchwald's S-Phos[19]) was used, dichloride **13** underwent coupling with 1,4-benzenediboronic acid bis(pinacol) ester **14** followed by subsequent macrocyclization in one pot to deliver **15** in 8% yield.[20]

The proton NMR spectrum of macrocycle **15** revealed some intriguing conformational features (Figure 3). Eight aromatic protons (H_A and H_B) are much further upfield (∼6.4 and ∼6.6 ppm) than is observed in the larger macrocycles **3**, **4**, and **5** (7.2 ppm). As can be seen in both the X-ray structure and the density functional theory (DFT)-optimized geometry of **15**, the protons on the biphenyl moiety are oriented into the ring current shielding cones of the aromatic rings across the macrocycle. The four protons ortho to the cyclohexadiene units (H_A) are ca. 2.7 Å from the face of the adjacent aryl ring (Ar_1), leading us to identify these as the most upfield protons. The four protons meta to the cyclohexadiene units (H_B) are ca. 4.0 and 4.8 Å from aryl rings Ar_1 and Ar_2 respectively, placing them farther from an aromatic shielding cone and thus more downfield than H_A.[21] The number of signals and splitting patterns in the NMR spectrum indicate that the aryl rings in the biphenyl moiety are freely rotating. This edge-to-face orientation places the electrostatically negative edges of the biphenyl aryl rings into the electrostatically positive faces of the opposing aromatic units. This interaction is known to lead to ca. 2 kcal/mol of stabilization energy and possibly explains why the smaller macrocycle orients in this fashion.[22]

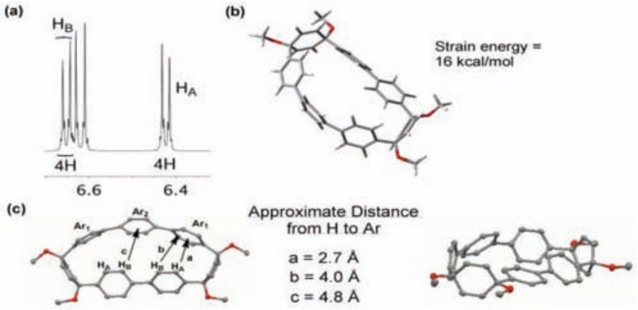


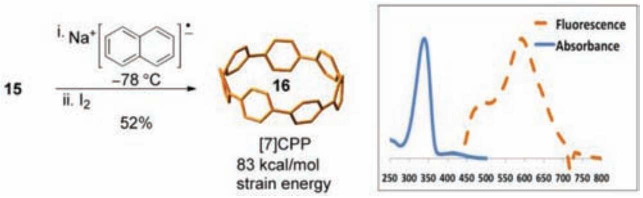
Figure 3. (a) ^1H NMR spectrum, (b) DFT-optimized geometry, and (c) crystal structure of macrocycle **15**.[21]

We probed the relative strain energy of macrocycle **15** using DFT calculations[23] and isodesmic reactions.[24] Macrocycle **4** requires a buildup of only 3.2 kcal/mol of strain energy in the cyclization step, whereas macrocycle **15** requires 16 kcal/mol of strain energy.[25] These results are consistent with the more challenging cyclization to generate **15**.

With macrocycle **15** in hand, we investigated our reductive aromatization reaction.[26] Subjecting **15** to sodium naphthalenide at −78 °C led to [7]CPP (**16**) in 52% yield (Scheme 3). As the reaction proceeded, we observed a change to a deep-purple solution and attribute this to the radical anion of **16**. We have observed this with other CPPs as well and therefore quench these reactions with a solution of iodine in order to avoid additional side reactions.[27] Impressively, this single reaction builds ca. 67 kcal/mol of additional strain energy into the [7]CPP structure at −78 °C. The proton NMR spectrum of **16** shows a singlet at 7.48 ppm, similar to what is observed for other CPPs and indicating free rotation of the aryl rings on the NMR time scale.[4] The DFT-optimized geometry shows dihedral angles ranging from 12.9 to 30.7°, consistent with the studies by Wong.[28] The calculated bond lengths are similar to the experimental values for larger CPPs: 1.39 Å for the $C_{ortho}-C_{ortho}/C_{ipso}-C_{ortho}$ bonds and 1.49 Å for the $C_{ipso}-C_{ipso}$ bonds, suggesting benzenoid character.[8]

The optical absorption and emission spectra of [7]CPP are illustrated in Scheme 3.[29] [7]CPP has a dominant absorption maximum at 339 nm, similar to those in all other cycloparaphenylenes.[4,10] The insensitivity of this strong absorption to the

Scheme 3. Aromatization and Optical Characterization of [7]CPP



size of the CPP is a unique feature that has been rationalized theoretically by Yamago and co-workers.[10] The difference in HOMO and LUMO energies of the CPPs narrows as the size decreases because of the more quinoid-like structure of smaller, strained CPPs.[30] This narrowing of the HOMO−LUMO gap with decreasing size, however, is not relayed into the observed optical absorption maxima. The postulated reason for this is that the HOMO−LUMO transition has either no or very little oscillator strength for these structures. Accordingly, Yamago illustrated that the absorption maxima can be best rationalized on the basis of a summation of other filled-to-unfilled transitions (e.g., HOMO to LUMO+1, HOMO−1 to LUMO, etc.), which are relatively insensitive to size. We observed a smaller absorption centered at 410 nm that may correspond to the HOMO−LUMO transition of [7]CPP. The corresponding emission has a maximum at 592 nm with a low quantum yield of 0.007, as expected for a relatively forbidden transition.[25] Interestingly, we have measured the quantum yield of [12]CPP to be 0.81, suggesting an increasingly allowed transition with increasing CPP size. The size-dependent fluorescence pathways of the CPPs warrant further photophysical studies.

In conclusion, we have developed the first synthesis of [7]CPP utilizing an orthogonal Suzuki−Miyaura coupling strategy. This cycloparaphenylene has a strain energy of 83 kcal/mol and an orange fluorescence at 592 nm. The size-dependent optical behavior of the [*n*]CPPs positions them as interesting candidates for a new class of "carbon quantum dots". Efforts are underway in our laboratory to prepare the more strained [6]CPP and exploit the CPP scaffolds as interesting optoelectronic materials for a wide range of applications.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Syntheses and characterization of all new compounds, geometries and strain energies determined by DFT calculations, complete ref 23, and crystallographic data for **15** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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