

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

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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 dots¹¹ 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

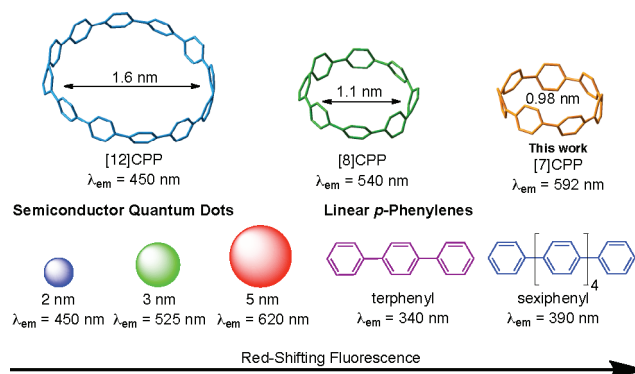


Figure 1. Size-dependent fluorescence of cycloparaphenylenes, quantum dots, and linear p -phenylenes.

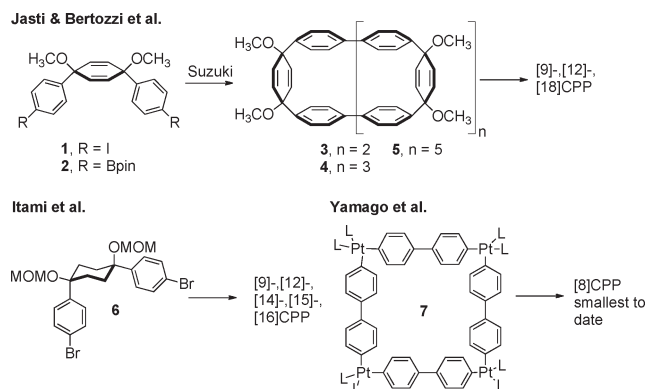


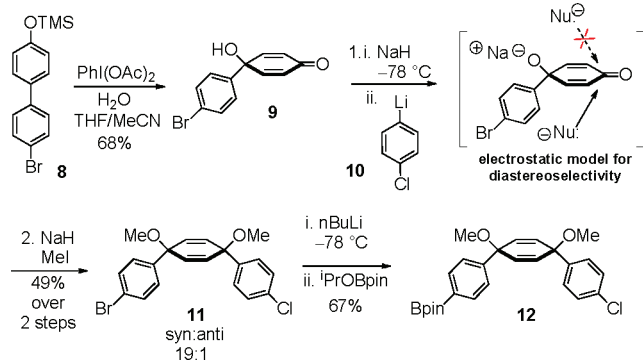
Figure 2. Previous synthetic routes are not amenable to smaller CPPs.

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.

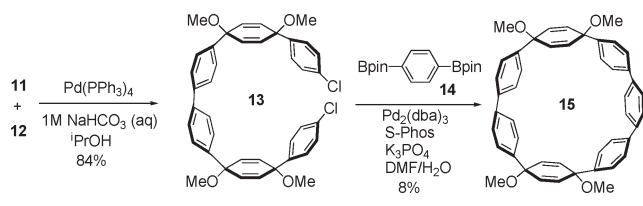
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Scheme 1. Preparation of Monomers 11 and 12



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 H₂O 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 > CH₃O), 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-Phos¹⁹) 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

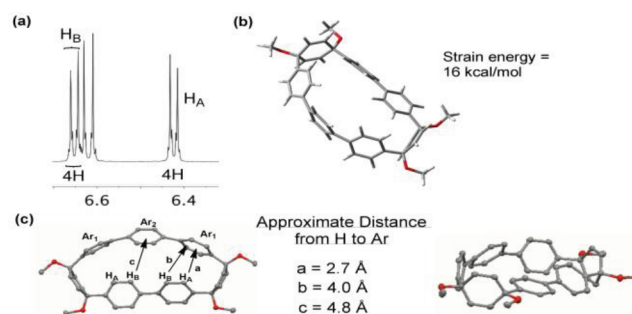


Figure 3. (a) ¹H NMR spectrum, (b) DFT-optimized geometry, and (c) crystal structure of macrocycle 15.²¹

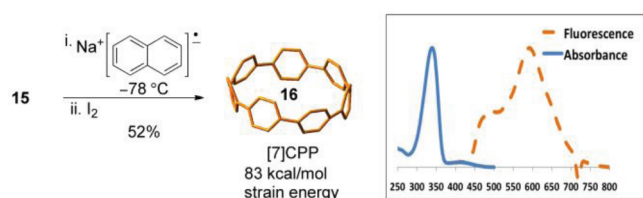
protons (H_A and H_B) are much further upfield (~6.4 and ~6.6 ppm) than is observed in the larger macrocycles 3, 4, and 5 (7.2 ppm). As can be seen in both the X-ray structure and the density functional theory (DFT)-optimized geometry of 15, the protons on the biphenyl moiety are oriented into the ring 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 (Ar₁), 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 Ar₁ and Ar₂ 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

We probed the relative strain energy of macrocycle 15 using DFT calculations²³ 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

S 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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■ REFERENCES

- (1) Jasti, R.; Bertozzi, C. R. *Chem. Phys. Lett.* **2010**, 494, 1.
- (2) Fort, E. H.; Scott, L. T. *J. Mater. Chem.* **2011**, 21, 1373.
- (3) For a review of CNT structure, see: Saito, R.; Dresselhaus, G.; Dresselhaus, M. S. *Physical Properties of Carbon Nanotubes*; Imperial College Press: London, 1998.
- (4) Jasti, R.; Bhattacharjee, J.; Neaton, J. B.; Bertozzi, C. R. *J. Am. Chem. Soc.* **2008**, 130, 17646.
- (5) Takaba, H.; Omachi, H.; Yamamoto, Y.; Bouffard, J.; Itami, K. *Angew. Chem., Int. Ed.* **2009**, 48, 6112.
- (6) Yamago, S.; Watanabe, Y.; Iwamoto, T. *Angew. Chem., Int. Ed.* **2010**, 49, 757.
- (7) Omachi, H.; Matsuura, S.; Segawa, Y.; Itami, K. *Angew. Chem., Int. Ed.* **2010**, 49, 10202.
- (8) Segawa, Y.; Miyamoto, S.; Omachi, H.; Matsuura, S.; Senel, P.; Sasamori, T.; Tokitoh, N.; Itami, K. *Angew. Chem., Int. Ed.* **2011**, 50, 3244.
- (9) Segawa, Y.; Senel, P.; Matsuura, S.; Omachi, H.; Itami, K. *Chem. Lett.* **2011**, 40, 423.
- (10) Iwamoto, T.; Watanabe, Y.; Sakamoto, Y.; Suzuki, T.; Yamago, S. *J. Am. Chem. Soc.* **2011**, 133, 8354.
- (11) Gaponenko, S. V. *Optical Properties of Semiconductor Nanocrystals*; Cambridge University Press: Cambridge, U.K., 1998.
- (12) Nijegorodov, N. I.; Downey, W. S.; Danailov, M. B. *Spectrochim. Acta, Part A* **2000**, 56, 783.
- (13) Bijl, V.; Itoh, T.; Ishikawa, M. *Chem. Soc. Rev.* **2010**, 39, 3031.
- (14) Resch-Genger, U.; Grabolle, M.; Cavaliere-Jaricot, S.; Nitschke, R.; Nann, T. *Nat. Methods* **2008**, 9, 763.
- (15) A similar strategy had been suggested earlier for the synthesis of cyclophynes. See: Srinivasan, M.; Sankararaman, S.; Hopf, H.; Varghese, B. *Eur. J. Org. Chem.* **2003**, 660.
- (16) Liu, Q.; Rovis, T. *Org. Process Res. Dev.* **2007**, 11, 598.
- (17) Wipf, P.; Jung, J. *Chem. Rev.* **1999**, 99, 1469.
- (18) Littke, A. F.; Fu, G. C. *Angew. Chem., Int. Ed.* **2002**, 41, 4176.
- (19) Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, 127, 4685.
- (20) The byproducts of this reaction were linear oligomers.
- (21) Because of the extreme insolubility of macrocycle 15 and the resultant difficulty of growing crystals of substantial size, the crystal structure obtained was not resolved sufficiently to allow accurate measurements of distance. The optimized geometry from the DFT calculations was used for all distances, while the X-ray crystal data provided conformational information.
- (22) Anslyn, E.; Dougherty, D. *Aromatic–Aromatic Interactions (π Stacking)*. In *Modern Physical Organic Chemistry*; University Science Books: Mill Valley, CA, 2008; p 184.
- (23) Frisch, M. J.; et al. *Gaussian 03*, revision C.02; Gaussian, Inc.: Wallingford, CT, 2004.
- (24) Takaba, H.; Omachi, H.; Yamamoto, Y.; Bouffard, J.; Itami, K. *Angew. Chem., Int. Ed.* **2009**, 48, 6112.
- (25) For full details, see the Supporting Information.
- (26) For further details, see ref 4.
- (27) Rickhaus, M.; Belanger, A.; Wegner, H.; Scott, L. T. *J. Org. Chem.* **2010**, 75, 7358.
- (28) Wong, B. *J. Phys. Chem. C* **2009**, 113, 21921.
- (29) The spectra were acquired with dichloromethane as the solvent.
- (30) Jagadeesh, M. *J. Mol. Model.* **2000**, 6, 226.