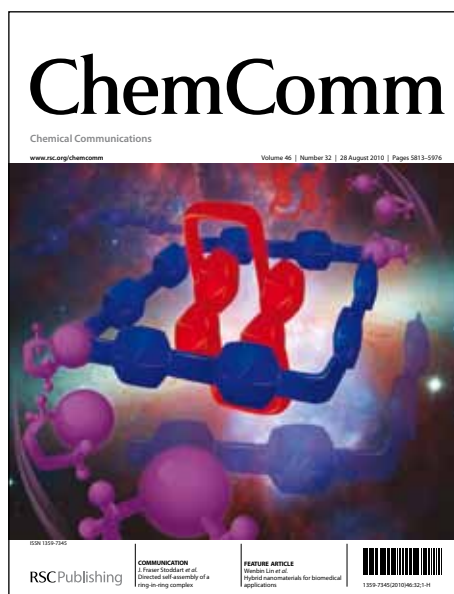


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COMMUNICATION

Selective Synthesis of [7]- and [8]Cycloparaphenylenes

Cite this: DOI: 10.1039/x0xx00000x

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Received 00th January 2012,

Accepted 00th January 2012

DOI: 10.1039/x0xx00000x

www.rsc.org/

Cycloparaphenylenes (CPPs) are a remarkable class of hoop-shaped conjugated macrocycles with inimitable properties. Herein we describe a divergent synthesis of [7]CPP and [8]CPP. Furthermore we present the first crystal structure of [7]CPP. Thus, we now have established the size-selective synthesis of [n]CPP (n = 7–16) in a uniformed cyclohexane-based method.

Synthesis and characterization of belt-shaped conjugated systems, as well as their unique properties and their potential applications captivated scientists for decades.¹ The creation of cycloparaphenylenes (CPPs),² especially, gained significant interest due to their simple structure and the representation of the shortest sidewall segment of armchair carbon nanotubes (CNT).^{11,3} Since the first successful synthesis of CPP by Bertozzi *et al.*,⁴ a variety of synthetic routes from the groups of Itami,^{5–10} Yamago,^{11–14} and Jasti^{4,15–19} have been published and [n]CPPs, where n is 6–16 have been synthesized. Moreover photophysical,^{4,11,12,15,16,19} optical^{20,21} and electronic^{1b,6,22–26} properties as well as guest-encapsulating properties^{8,9,27} were investigated. More recently, we demonstrated the size-selective growth of CNT from a CPP template.²⁸ Herein, we report a size-selective synthesis of [7]- and [8]CPP by a modular approach and present the first X-ray crystal structure of [7]CPP.

We previously reported the size-selective synthesis of [n]CPP (n = 9–16).^{5,7,10} The key step of these syntheses is the formation of strain-free triangle and square precursors from the terphenylene-convertible L-shaped unit and linear units such as 1,4-diborylbenzene or 4,4'-diborylbiphenyl. Although this methodology had an advantage to synthesize larger size [n]CPPs (n ≥ 9), it could not be applied to smaller CPPs. Therefore, we decided to develop a new arylcyclohexanone building block for the synthesis of [7]- and [8]CPP (Fig. 1). After the formation of a C-shaped unit from a L-shaped unit and arylcyclohexanone, a nickel-mediated intramolecular C–Br/C–Br coupling should produce the macrocyclic precursor of [7]CPP. On the other hand, the reaction of the same intermediate in a palladium-catalyzed C–B/C–Br intermolecular cross-coupling reaction will lead to [8]CPP. This modular route to [7]- and [8]CPP shows the advantage that only one intermediate, the acyclic C-shaped unit, is necessary to synthesize both CPPs. In

addition, cyclic precursors have less strain (see ESI). From the hypothetical homodesmotic reaction, the strain energies of triangular [7]- and [8]CPP precursors are 8.6 kcal·mol⁻¹ and 10.4 kcal·mol⁻¹, respectively, whereas [7]- and [8]CPP have much higher strain energy, 84.0 kcal·mol⁻¹ and 72.2 kcal·mol⁻¹, respectively.⁶

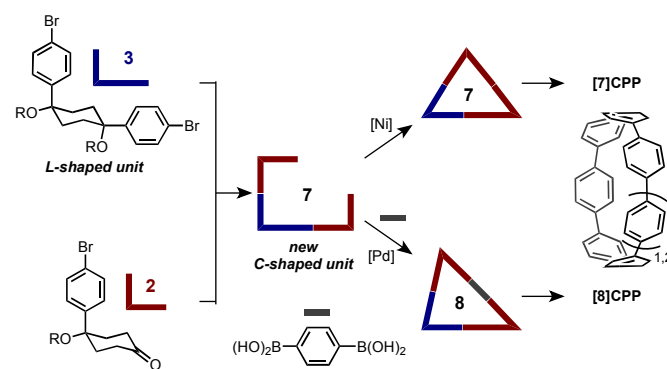
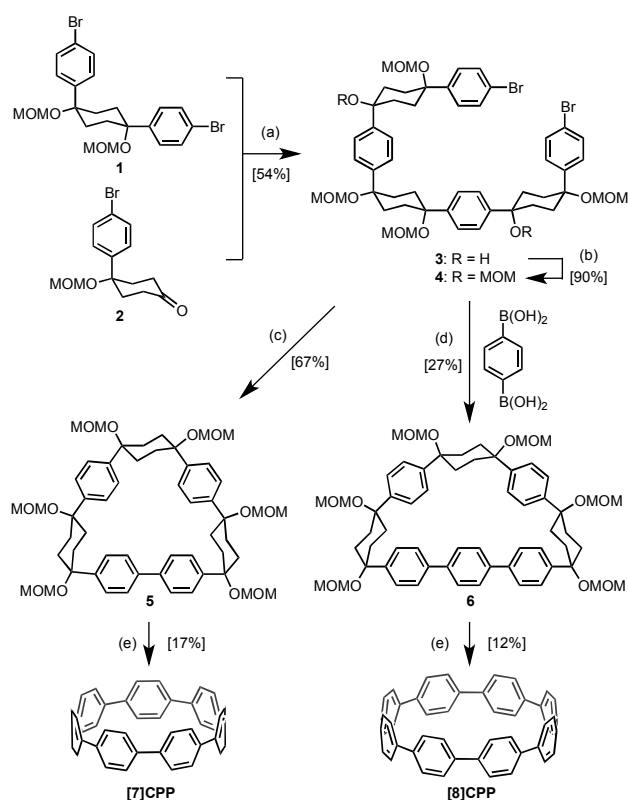


Fig. 1 Modular approach to [7]- and [8]CPP.

We started from our previously used L-shaped unit **1** and the newly developed 4-bromophenyl-4-methoxymethoxycyclohexanone (**2**), which is readily available *via* a two-step reaction from 1,4-dibromobenzene and 1,4-cyclohexanedione-monoethyleneketal (for further information see ESI). The twofold addition of dilithiated **1** to **2** afforded the C-shaped unit **3**. A subsequent MOM-protection led to the desired precursor **4** for the following macrocyclization steps. The synthesis of [7]CPP was possible under cost-efficient conditions, using our previously reported nickel-mediated C–Br/C–Br coupling^{8–10} in an intramolecular fashion. The macrocycle **5** was obtained in 67% yield. In case of [8]CPP, a palladium-catalyzed intermolecular cross-coupling of **4** with 1,4-benzenediboric acid led to the desired macrocycle **6** in 27% yield. The treatment of **5** and **6** with NaHSO₄ under air facilitated the aromatization to furnish [7]CPP and [8]CPP in 17% and 12% yield, respectively. The total yield over six steps for [7]CPP was 4.6%, which is rather high compared to the previous report by Jasti *et al.* (eight steps, 1.5% yield)¹⁸ whereas total yield of [8]CPP (1.0%) was lower.



Recrystallization of [7]CPP from a chloroform/cyclohexane solution at room temperature afforded yellow single crystals which were suitable for X-ray crystallography. Fig. 2 shows the ORTEP drawing of the first crystal structure of [7]CPP, which forms a circular structure in the solid state. A disordered cyclohexane molecule was incorporated within the ring of [7]CPP. The packing mode of [7]CPP shows a herring bone type structure (Fig. 3), which was also observed in [8]-, [9]-, [10]-, and [12]CPP.^{8,9,13,17} Although only [6]CPP was aligned as tubular structure,¹⁶ it is still unclear what affects the alignment of CPPs in the solid state.

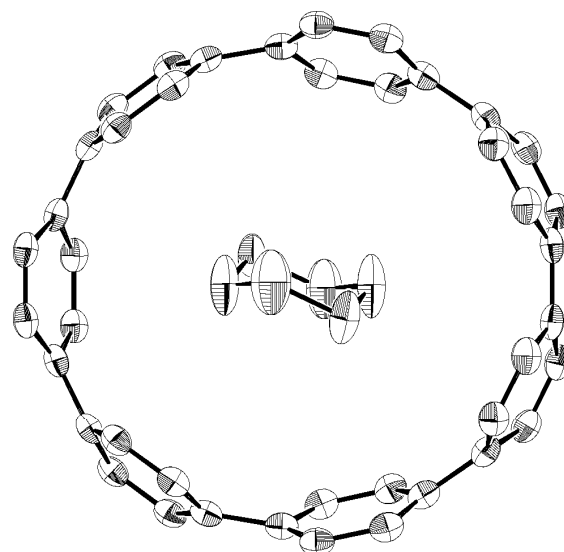


Fig. 2 ORTEP drawing of [7]CPP-cyclohexane with 50% thermal ellipsoids. All hydrogen atoms and the other part of disordered cyclohexane molecule are omitted for clarity. Half of the entire structure constitutes an asymmetric unit.

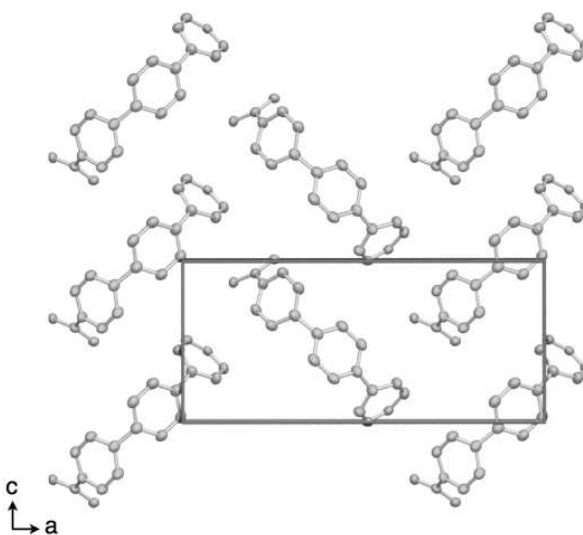


Fig. 3 Packing structure of [7]CPP-cyclohexane. A unit cell is shown as a rectangle.

The optical absorption and emission spectra of [7]- and [8]CPP in a chloroform solution are illustrated in Fig. 4. In the UV-vis absorption spectra, [7]- and [8]CPP exhibited shoulder-like absorption bands in the long-wavelength region around 400–420 nm in addition to the intense absorption bands with the absorption maximum wavelengths of 338–340 nm similar to other sizes of CPPs.¹⁹ The CPPs we synthesized gave almost the same absorption and fluorescence spectra as those reported by Jasti¹⁵ and Yamago¹¹ although the fluorescence spectrum of [7]CPP was slightly different from the reported one. The solution of [7]CPP shows very weak yellow fluorescence whereas [8]CPP shows green fluorescence excited at the absorption maximum wavelengths.

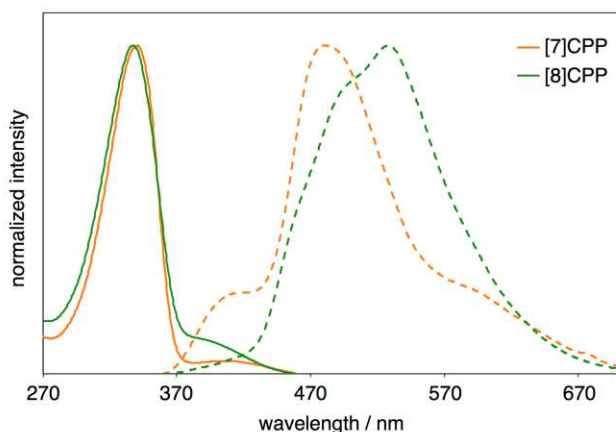


Fig. 4 Absorption (solid curves) and fluorescence (broken curves) spectra of [7]- and [8]CPP.

In summary, we have established a divergent and size-selective synthetic route to [7]CPP and [8]CPP. The overall yield of [7]CPP from commercially available starting materials is 2.4% over six steps. The X-ray crystal structure of [7]CPP, which was obtained for the first time, shows the same packing mode as larger CPPs, as well as the same tendency in bond alternations. The synthesis of [8]CPP was possible in a cost-efficient fashion. Thus, we now have established the size-selective synthesis of [n]CPP ($n = 7-16$) in a uniformed cyclohexane-based method.

This work was supported by the Funding Program for Next Generation World-Leading Researchers from JSPS (220GR049 to K.I.). F.S. thanks the International Research Training Group Münster/Nagoya for support. K.M. is the recipient of JSPS research fellowship for young scientists. Calculations were performed using the resources of the Research Center for Computational Science, Okazaki, Japan. ITbM is supported by the World Premier International Research Center (WPI) Initiative, Japan.

Notes and references

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Electronic Supplementary Information (ESI) available: Experimental procedures, spectra of new compounds, and details of computational studies. CCDC 963468 ([7]CPP-cyclohexane). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c000000x/

- Reviews: a) T. Kawase and C. Kurata, *Chem. Rev.*, 2006, **106**, 5250; b) K. Tahara and Y. Tobe, *Chem. Rev.*, 2006, **106**, 5274; c) B. D. Steinberg and L. T. Scott, *Angew. Chem. Int. Ed.*, 2009, **48**, 5400, d) L. T. Scott, *Angew. Chem. Int. Ed.*, 2003, **42**, 4133; e) T. Yao, H. Yu, R. J. Vermeiji and G. J. Bodwell, *Pure Appl. Chem.*, 2008, **80**, 533; f)

- K. Itami, *Pure Appl. Chem.*, 2012, **84**, 907; g) M. Iyoda, J. Yamakawa and M. J. Rahman, *Angew. Chem. Int. Ed.*, 2011, **50**, 10522.
- a) V. C. Parckh and P. C. Guha, *J. Indian Chem. Soc.*, 1934, **11**, 95; b) R. Friederich, M. Nieger and F. Vögtle, *Chem. Ber.*, 1993, **126**, 1723.
- H. Omachi, Y. Segawa and K. Itami, *Acc. Chem. Res.*, 2012, **45**, 1378.
- R. Jasti, J. Bhattacharjee, J. B. Neaton and C. Bertozzi, *J. Am. Chem. Soc.*, 2008, **130**, 17646.
- H. Takaba, H. Omachi, Y. Yamamoto, J. Bouffard and K. Itami, *Angew. Chem. Int. Ed.*, 2009, **48**, 6112.
- Y. Segawa, H. Omachi and K. Itami, *Org. Lett.*, 2010, **12**, 2262.
- H. Omachi, S. Matsuura, Y. Segawa and K. Itami, *Angew. Chem. Int. Ed.*, 2010, **49**, 10202.
- Y. Segawa, S. Miyamoto, H. Omachi, S. Matsuura, P. Šenel, T. Sasamori, N. Tokitoh and K. Itami, *Angew. Chem. Int. Ed.*, 2011, **50**, 3244.
- Y. Segawa, P. Šenel, S. Matsuura, H. Omachi and K. Itami, *Chem. Lett.*, 2011, **40**, 423.
- Y. Ishii, Y. Nakanishi, H. Omachi, S. Matsuura, K. Matsui, H. Shinohara, Y. Segawa and K. Itami, *Chem. Sci.*, 2012, **3**, 2340.
- S. Yamago, Y. Watanabe and T. Iwamoto, *Angew. Chem. Int. Ed.*, 2010, **49**, 757.
- T. Iwamoto, Y. Watanabe, Y.-I. Sakamoto, T. Suzuki and S. Yamago, *J. Am. Chem. Soc.*, 2011, **133**, 8354.
- E. Kayahara, Y. Sakamoto, T. Suzuki and S. Yamago, *Org. Lett.*, 2012, **14**, 3284.
- E. Kayahara, T. Iwamoto, T. Suzuki and S. Yamago, *Chem. Lett.*, 2013, **42**, 621.
- T. J. Sisto, M. R. Golder, E. S. Hirst and R. Jasti, *J. Am. Chem. Soc.*, 2011, **133**, 15800.
- J. Xia and R. Jasti, *Angew. Chem. Int. Ed.*, 2012, **51**, 2474.
- J. Xia, J. W. Bacon and R. Jasti, *Chem. Sci.*, 2012, **3**, 3018.
- E. R. Darzi, T. J. Sisto and R. Jasti, *J. Org. Chem.*, 2012, **77**, 6624.
- Y. Segawa, A. Fukazawa, S. Matsuura, H. Omachi, S. Yamaguchi, S. Irle and K. Itami, *Org. Biomol. Chem.*, 2012, **10**, 5979.
- T. Nishihara, Y. Segawa, K. Itami, and Y. Kanemitsu, *J. Phys. Chem. Lett.*, 2012, **3**, 3125.
- C. Camacho, T. A. Niehaus, K. Itami and S. Irle, *Chem. Sci.*, 2013, **4**, 187.
- M. N. Jagadeesh, A. Makur and J. Chandrasekhar, *J. Mol. Model.*, 2000, **6**, 226.
- B. M. Wong, *J. Phys. Chem. C*, 2010, **12**, 2751.
- D. Sundholm, S. Taubert and F. Pichierri, *Phys. Chem. Chem. Phys.*, 2010, **12**, 2751.
- S. Taubert, D. Sundholm and F. Pichierri, *J. Org. Chem.*, 2010, **75**, 5867.
- S. M. Bachrach and D. Stuck, *J. Org. Chem.*, 2010, **75**, 6595.
- T. Iwamoto, Y. Watanabe, T. Sadahiro, T. Haino and S. Yamago, *Angew. Chem. Int. Ed.*, 2011, **50**, 8342.
- H. Omachi, T. Nakayama, E. Takahashi, Y. Segawa and K. Itami, *Nature Chem.*, 2013, **5**, 572.