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Half-substituted fluorocycloparaphenylenes with high symmetry: Synthesis, properties and derivatization to densely substituted carbon nanorings

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Fluorinated cycloparaphenylenes (FCPPs) have attracted attention as electron-accepting CPPs as well as strained fluoroarenes. Herein, we report the synthesis and properties of novel FCPPs; $F_{16}[8]$ CPP and $F_{12}[6]$ CPP. Furthermore, the derivatization of $F_{16}[8]$ CPP afforded a new carbon nanoring where sixteen pyrrole rings are densely substituted on CPP framework.

$[n]$ Cycloparaphenylene ($[n]$ CPP) is a macrocyclic molecule where n benzene rings are connected in their *para*-positions (Fig. 1a, left).¹ After the synthesis has been achieved in late 2000s,² the chemistry of CPPs has dramatically advanced by a number of chemists attracted with the distinctive characters of CPPs such as highly strained structures and electronic properties generated by circularly conjugated system.^{1,3} Among CPP families, fluorinated CPPs (FCPPs) represent recent hot targets since they are not only new substituted CPPs but also rarely synthesized strained fluoroarenes (Fig. 1b).^{4–6} In 2018, the group of Yamago has opened the chemistry of FCPPs by the synthesis of partially fluorinated CPPs (parFCPPs), $F_8[6]$ CPP and $F_{12}[9]$ CPP through the formation of macrocyclic Pt complexes followed by reductive aromatization of tetrafluorocyclohexadiene units.⁷ Jasti and coworkers also reported the synthesis of parFCPPs, $F_8[10]$ CPP, $F_8[12]$ CPP and $F_{12}[12]$ CPP, via tetrafluorobenzene and cyclohexadiene moieties containing macrocycle.^{8,9} By introducing fluoroarenes to CPPs, parFCPPs have gained distinctive properties such as blue-shifted fluorescence, low-lying molecular orbitals, and tubular packing structures. However, these parFCPPs

incorporate non-fluorinated phenylene units because the fluoroarene sites are introduced sequentially. Thus, fluorine atoms are undistributed on the CPP rings, resulting in their low structural symmetry.

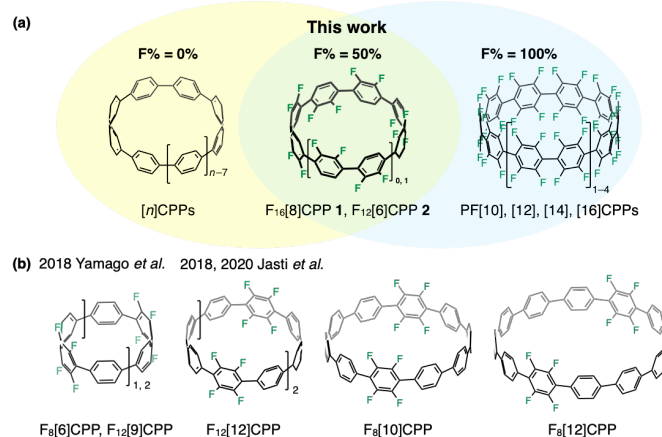


Fig. 1 (a) Difference of fluorine-containing percentage (F%) between CPPs. (b) Partially fluorinated CPPs.

Recently, we have synthesized perfluoro $[n]$ CPPs (PF $[n]$ CPPs, $n = 10, 12, 14, 16$), where all hydrogen atoms in CPPs are replaced with fluorine atoms (Fig. 1a, right).¹⁰ PF $[n]$ CPPs are FCPPs with D_{nd} symmetry, which exhibit wide HOMO–LUMO gaps, high reduction potentials, as well as strong phosphorescence at low temperature. Encouraged by the unique features of FCPPs, we next quested for a missing class of FCPP, parFCPPs with high symmetry. A half-substituted FCPP (percentage of fluorinated atoms against hydrogen atoms on CPPs ($F\%$) = 50%), whose structure stands in the middle of CPP ($F\%$ = 0%) and PFCPPs ($F\%$ = 100%), should be an intriguing target to investigate not only to uncover the electronic fluorine effects but also to pave ways to access densely decorated carbon nanorings and nanobelts. Herein, we report the short-step synthesis of parFCPPs with $F\%$ of 50%, $F_{16}[8]$ CPP (1) and $F_{12}[6]$ CPP (2), where *ortho*-difluorophenylene units are circularly connected (Fig. 1a, middle). Their structural,

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photophysical, and electronic properties were uncovered and the successful derivatization of **1** to install 16 pyrrole rings onto the CPP framework was achieved.

We previously synthesized PF[*n*]CPPs via the formation of macrocyclic nickel complexes and subsequent oxidant-induced reductive elimination in a one-pot procedure.¹⁰ We envisioned that the synthetic method of PF[*n*]CPP can be applied for the rapid synthesis of **1** and **2**. Thus, 2,3,2',3'-tetrafluorobiphenyl (**3**) was deprotonated with lithium diisopropylamide (LDA) and then reacted with NiBr₂(dnbpy) (dnbpy = 4,4'-di-*n*-nonyl-2,2'-bipyridyl) to form macrocyclic complex. After replacing THF with *m*-xylene, 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ) was added, and the resulting mixture was stirred at 130 °C for 5 h to promote the aryl–aryl reductive elimination from the nickel complex. After purification with silica gel chromatography, F₁₆[8]CPP (**1**) was isolated in 0.7% yield (Fig. 2a). From the reaction mixture, very small mass signal corresponding to F₂₀[10]CPP was detected by LDI-TOF MS, along with linear fluorophenylenes with various lengths (see Supporting Information Fig. S2).

While our Ni-based method afforded **1**, other parFCPPs with different ring size were needed to investigate the ring-size effects in the properties. In 2020, the group of Tsuchido and Osakada reported a unique CPP synthesis via macrocyclic gold complexes.^{11,12} We found that the Tsuchido-Osakada method is suitable in the synthesis of F₁₂[6]CPP (**2**). Thus, (2,2',3,3'-tetrafluoro-[1,1'-biphenyl]-4,4'-diyl)diboronic acid was treated with [Au₂Cl₂(dcpm)] (dcpm = bis(dicyclohexylphosphino)methane) in the presence of Cs₂CO₃ (1:1:6 molar ratio) in toluene/ethanol/water at 50 °C to produce the corresponding hexagold(I) complex, [Au₂(C₆F₂H₂-C₆F₂H₂)(dcpm)]₃. The oxidant-induced reductive elimination of the hexagold(I) complex was conducted upon the addition of PhICl₂ in 1,2-dichloroethane at 150 °C^{13–15} to furnish **2** in 3.8% yield after preparative thin-layer chromatography (Fig. 2b).

In the ¹H NMR spectra, a broad singlet signal was observed at 7.05 ppm for **1** and one doublet signal was observed at 7.40 ppm for **2**, coupled with fluorine atoms (see SI for ¹H{¹⁹F} NMR). In the ¹⁹F NMR spectra, a broad singlet signal was observed at –140.58 ppm for **1** and sole singlet signal was observed at –140.68 ppm for **2**. Three singlet signals observed in the ¹³C{¹H, ¹⁹F} NMR spectra also agreed with the highly symmetric structures of these F_{2*n*}[*n*]CPPs.

Since single crystals of **1** and **2** were obtained from benzene/*n*-hexane and THF/*n*-pentane, respectively, their structures were successfully determined by X-ray crystallography. As shown in left of Fig. 2c and d, circularly connected eight and six *ortho*-difluorophenylene units were unambiguously confirmed, where benzene (for **1**) or THF (for **2**) used for recrystallization were contained inside the CPP ring. Likely due to the steric repulsion caused by fluorine atoms, the directions of *ortho*-difluorophenylene units are alternately arranged. The crystal packing structures of **1** and **2** are shown in right of Fig. 2c and d. The alignment of **1** and **2** are gear-like and brick-wall packing respectively, whereas the previously reported parFCPPs and PFCPPs have tubular packing and pristine CPPs have herringbone-like packing except for the

tubular packing of [6]CPP.¹⁶ This clearly indicates that the influence of fluorine and hydrogen atoms is significant on the molecular alignment in crystalline state. The average torsion angle between neighboring benzene rings observed in X-ray crystallography in **1** was larger than that of **2** (**1**: 36.8°; **2**: 27.4°). In addition, the average torsion angle of **2** was smaller than that of pristine [6]CPP (28.1°, see Supplementary Table S2).^{16–18} Noncovalent interaction (NCI) plots suggest that the small torsion angles, especially in the crystal of **2**, are due to H–F interactions between neighboring benzene rings (see Fig. S14 and Fig. S15). Similarly, stronger intramolecular interactions were suggested for **1** than [8]CPP (see Supplementary Fig. S16, S17). In comparison with PF[6] and [8]CPPs, the torsion angles of **1** and **2** are smaller than those of PF[6] and [8]CPPs optimized at the B3LYP/6-31+G(d) scrf CHCl₃ (PF[6]CPP: 47.3°; PF[8]CPP: 52.4°, see Supplementary Table S2).

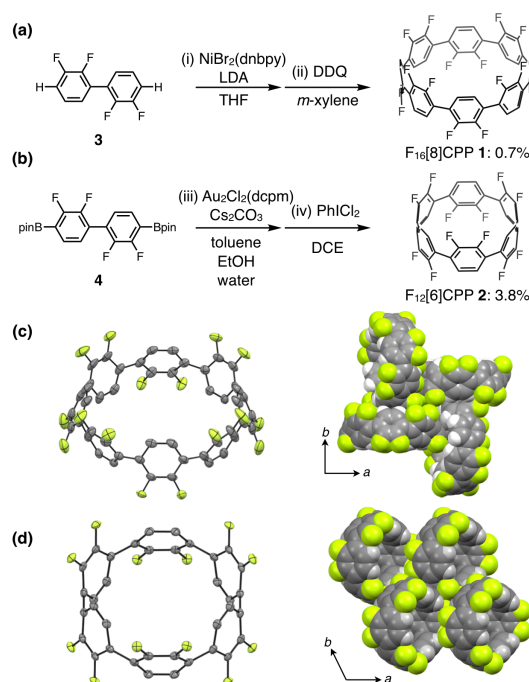


Fig. 2 (a) Synthesis of **1**: (i) **3** (1.0 equiv.), NiBr₂(dnbpy) (1.0 equiv.), LDA (4.0 equiv.), THF, –78 °C, 30 min, then evaporated. (ii) mixture product of (i), DDQ (5.0 equiv.), *m*-xylene, 130 °C, 5 h. (b) Synthesis of **2**: (iii) **4** (1.0 equiv.), Au₂Cl₂(dcpm) (1.0 equiv.), Cs₂CO₃ (6.0 equiv.), toluene/EtOH/water = 4:1:1, 50 °C, 24 h. (iv) mixture product of (iii), PhICl₂ (3.0 equiv.), 1,2-dichloroethane, 150 °C, 3 h. (c, d) ORTEP and packing structure of **1** (c) and **2** (d) with thermal ellipsoids at 50% probability (hydrogen atoms are omitted for clarity). dnbpy: 4,4'-di-*n*-nonyl-2,2'-bipyridyl, LDA: lithium diisopropylamide, DDQ: 2,3-dichloro-5,6-dicyano-*p*-benzoquinone, dcpm: bis(dicyclohexylphosphino)methane, DCE: 1,2-dichloroethane.

To investigate the effect of fluorine atoms on the π -electrons in **1** and **2**, photophysical and electrochemical measurements as well as DFT calculations were carried out (Fig. 3c). The UV–vis absorption spectra showed that **1** and **2** have maximum absorption peaks at 300 nm and 320 nm, respectively. The absorption edges of **1** and **2** were observed at 400 nm and 460 nm, which are hypsochromically shifted compared to those of the corresponding CPPs and parFCPP ([8]CPP: 460 nm;^{2c} [6]CPP: 550 nm;^{16,17} F₈[6]CPP: 327 nm,⁷ see Supplementary Fig. S7, S8). In the fluorescence measurements, **1** showed rather

bright fluorescence at 458 nm with a quantum yield (Φ_F) of 0.52. The quantum yield is significantly lower than that of [8]CPP (Φ_F = 0.85) in dichloromethane (see Supplementary Fig. S7). The quantum yield of **1** was only somewhat reduced by partial introduction of fluorine atoms, whereas that of reported F_{12} [9]CPP is significantly reduced (e.g., F_{12} [9]CPP: Φ_F = 0.14, [9]CPP: Φ_F = 0.70).⁷ The fluorescence lifetime (τ) of **1** was found to be 4.26 ns. According to the equations $\Phi_F = k_r \times \tau$ and $k_r + k_{nr} = \tau^{-1}$, the radiative (k_r) and nonradiative (k_{nr}) decay rate constants from the singlet excited state were determined (k_r = 1.2×10^8 s⁻¹; k_{nr} = 1.1×10^8 s⁻¹). This difference is most likely caused by the introduction of fluorine atoms with high symmetry. On the other hand, **2** showed no fluorescence, which is similar to [6]CPP and F_8 [6]CPP.⁷

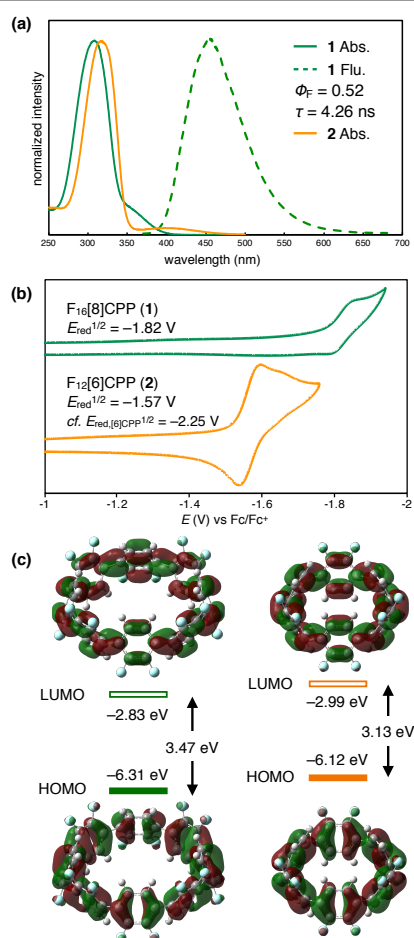


Fig. 3 (a) UV-Vis absorption (solid line), fluorescence spectra (dashed line) of **1** (green) and **2** (orange), quantum yield (Φ_F) and life time (τ) of **1**. (b) Cyclic voltammograms of **1** and **2** in acetonitrile (supporting electrolyte: [*n*-Bu₄N][PF₆]; scan rate: 0.1 V s⁻¹). Fc = ferrocene. (c) Frontier molecular orbitals (isovalue: 0.02) and their energies (eV) of **1** and **2** calculated by B3LYP/6-31+G(d) scrf CHCl₃ level of theory.

Next, cyclic voltammograms were recorded to gain more insight into the electronic properties of **1** and **2** (Fig. 3b). In acetonitrile, **1** and **2** showed a reduction potential (−1.82 V for **1** and −1.57 V for **2** vs ferrocene(II)/ferrocenium(III)). These values are higher than those of CPPs (e.g., [6]CPP: −2.25 V, [9]CPP: −2.45 V) and partially fluorinated CPPs (e.g., F_{12} [9]CPP: −1.79 V, F_{12} [9]CPP: −2.06 V),⁷ but lower than those of PFCPPs

(e.g., PF[*n*]CPP, *n* = 10, 12, 14: −1.23 V),¹⁰ indicating that the half-substitution by fluorine atoms affords an intermediate nature between non-fluorinated and fully fluorinated CPPs. Fig. 3c shows the HOMO and LUMO of **1** and **2** with their energies calculated at B3LYP/6-31+G(d) scrf CHCl₃ level of theory (for detail, see Supplementary Fig. S12, S13). While the shape and distribution of each frontier molecular orbital of **2** are almost identical to those of [6]CPP, the HOMO–LUMO gap is wider (**2**: 3.13 eV) than that of [6]CPP (3.03 eV), which is in line with the hypsochromic shift in the absorption spectra and the reduction potential.

Since **1** and **2** have multiple C–F bonds with high symmetry, we envisioned that these molecules would be enabling starting materials for a variety of densely substituted CPPs through C–F functionalization.²⁰ Based on this concept, we synthesized hexadecapyrrolyl[8]CPP **5** by S_NAr reaction of **1**. S_NAr reaction of pyrrole to C–F bonds of decafluorobiphenyl is known to proceed very efficiently, even when giving sterically crowded products.^{20,21} Thus, S_NAr reaction of **1** with pyrrole was conducted with sodium hydride at 50 °C in DMF (Fig. 4a). Gratifyingly, the desired reaction proceeded to afford **5**, which is a CPP with sixteen 1-pyrrolyl substitutions from **1**, in 29% yield in one step. Despite the substitution of sterically demanded pyrrole on the ring, the reaction proceeded with high efficiency of 93% per C–N bond formation.

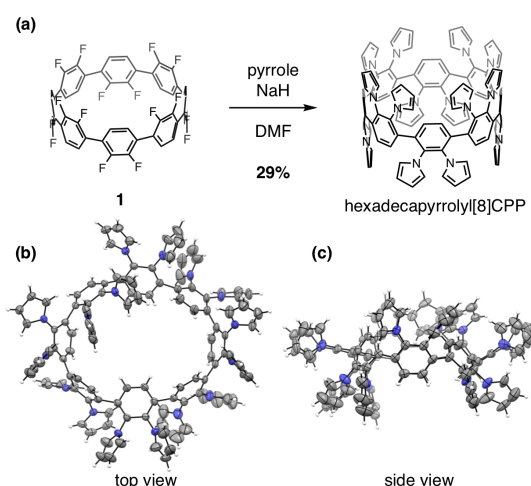


Fig. 4 (a) Synthesis of **5**: **1** (1.0 equiv.), pyrrole (32 equiv.), NaH (40 equiv.), DMF, 50 °C, 22 h. (b,c) Top view (b) and side view (c) of ORTEP structure of **5** with thermal ellipsoids at 50% probability.

We next investigated the structural and electronic properties of the thus-obtained **5**. Single crystals were obtained from toluene/*n*-pentane to reveal the structure of **5** by X-ray crystallography (Fig. 4b). The 16 substituted pyrrolyl groups are densely attached on the CPP ring. **5** has large torsion angles due to the large steric hindrance caused by the pyrrolyl groups, which is the largest average torsion angle (θ = 64.5°) of any crystal structures of carbon nanorings ever observed (for details, see Supplementary Fig. S6, Table S2).^{23,24} In the crystal structure, the substituted pyrrolyl groups are not alternately located above and below each other, and some of them are inside the CPP ring, resulting in low symmetry of the crystal structure of **5**.

NCI plots in the X-ray structure of **5** suggested intramolecular interactions among the pyrrolyl groups and CH- π interactions between the CPP moiety and encapsulated toluene, which might cause complicated conformation of **5** (for details, see Fig. S18, S19).²⁵ Actually, the ¹H NMR spectrum of **5** is complicated in CDCl₃ and DMSO-*d*₆, which is also consistent with examples of pyrrolyl substitution in cyclic compounds.²² We hypothesized that this was caused by various conformations of **5** due to densely substituted pyrrolyl groups. Thus, variable-temperature ¹H NMR (VT-¹H NMR) measurements were performed. In the ¹H NMR spectra of **5** in DMSO-*d*₆ at 20 °C to 150 °C, the number of signals decreased, however, the broad peaks were not resolved. When the ¹H NMR measurement was performed again at room temperature, the original spectra were observed, indicating that **5** was not decomposed at 150 °C and the VT-¹H NMR spectra were derived from **5** (for details, see Supplementary Fig. S41, S42). Since highly substituted carbon nanorings are attractive synthetic targets,^{23,24,26} it is remarkable that densely substituted carbon nanorings, which cannot be attributed to NMR spectra, were synthesized in only single reaction operation.

In summary, we have synthesized half-substituted fluorocycloparaphenylenes with high symmetry, F_{2n}[*n*]CPPs **1** and **2** via the formation of macrocyclic nickel and gold complexes and subsequent oxidant-promoted aryl-aryl reductive elimination. Photophysical and electrochemical measurements revealed the high reduction potential of F_{2n}[*n*]CPPs in comparison to CPPs. Remarkably, S_NAr reaction of **1** with pyrrole gave densely substituted nanoring **5** in one step. This work would contribute not only to progress the chemistry of CPPs and fluoroarenes but also to provide new strategy for the synthesis of unprecedented nanoring and nanobelts.

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Conflicts of interest

There are no conflicts to declare.

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